DE-41 (MTS) ANMOL, FATIMAH, FAIZAN, MARRIAM

DESIGN, DEVELOPMENT AND ANALYSIS OF A WALL-CLIMBING ROBOT FOR CLEANING AND INSPECTION OF COAL-FIRED BOILERS

COLLEGE OF
ELECTRICAL AND MECHANICAL ENGINEERING
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY RAWALPINDI
2023

COLLEGE OF ELECTRICAL AND MECHANICAL ENGINEERING

DE-41 MTS

PROJECT REPORT

DESIGN, DEVELOPMENT AND ANALYSIS OF A WALL-CLIMBING ROBOT FOR CLEANING AND INSPECTION OF COAL-FIRED BOILERS

Submitted to the Department of Mechatronics Engineering
in partial fulfillment of the requirements
for the degree of

Bachelor of Engineering
in
Mechatronics
2023

Sponsoring DS:
Dr. Kunwar Faraz
Lec Usman Asad

LE Adnan Shuja

Submitted By:

Anmol Nisa

Fatimah Tahira Husain

M Faizan Altaf

Marriam Imran

ACKNOWLEDGMENTS

We would like to start by expressing our sincere gratitude to Dr Kunwar Faraz, our honored thesis advisor, for their immense advice, knowledge, and unwavering support during the study process. Their astute suggestions and leadership were crucial in determining the course and results of this investigation. We would like to thank the faculty of the College of EME, NUST, Sir Adnan Shuja and Sir Usman Asad, for their assistance and resources. The availability of the equipment and supplies needed for the course of the project has been crucial. We are humble because of our friends and family's consistent support, tolerance, and encouragement during this study. They have been a constant source of encouragement and motivation since they cherish us and believe in what we have accomplished. Finally, we would like to thank the academics, researchers, and writers whose influential works provided the theoretical foundation for our study. Their efforts have opened the door for fresh perspectives and technological breakthroughs. We want to express deep appreciation to everyone who helped with this research in any way. This significant academic project was completed successfully thanks to your help and cooperation.

ABSTRACT

The increasing demand for vertical wall work in industries, due to industrial upgrading and urbanization, has generated a need for efficient inspection and cleaning of vertical surfaces, e.g., massive coal-fired boilers. However, the traditional manual cleaning and inspection process is time-consuming, expensive, and dangerous that can result in potential casualties and significant economic loss. Therefore, Wall-Climbing Robots (WCRs), having the ability to maneuver on vertical surfaces, are increasingly becoming popular since they can perform automatic inspection and cleaning of boiler walls at a significantly faster/safer rate and at a lower cost. Recently, many automatic devices have emerged in literature, but no significant research on wall climbing robots is currently being done in Pakistan. This project aims to develop an indigenous wall-climbing robot, which will leverage permanent magnetic wheels to create a secure and stable grip that will ensure easy movement on vertical walls. The WCR is also fitted with a water jet system for cleaning sludge deposits and is equipped with a high-resolution camera for inspecting surfaces of boiler walls. Integrating these technologies in our solution enabled us to develop a cost-effective wall-climbing robot capable of efficiently performing inspection and cleaning of boiler walls/vertical surfaces.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 – INTRODUCTION

In this era of information and technology, humans are constantly looking for ways to simplify their manual labor. Today machines and robots have become an integral part of our daily life. They not only make our work easier and effective but also less time-consuming. Currently, extensive research is being performed on new methods to widen the scope of robotics and pave the way to new breakthroughs and advancements.

Industrial upgrading has led to an increased demand for vertical wall work in various industries including construction, transportation, petrochemical, nuclear energy, shipbuilding, etc. This has resulted in frequent accidents caused by high-altitude work. Furthermore, the aging problem of civil infrastructures including bridges, tunnels, and dams is inevitable. Therefore, it is critical to determine the structural integrity and deterioration levels, since failure in terms of tracking and predicting the health of these constructions might lead to tremendous tragedies in future. However, it is very challenging and costly to inspect surfaces that are not easily accessible, such as building walls or bridge pillars.

The current manual inspection is time consuming, expensive, and often dangerous. Moreover, the surveillance and inspection of the Oil tanks, coal-fired boilers and storage tanks of nuclear power plants are extremely difficult and dangerous. In addition, Window glasses of high-rise buildings are difficult to clean manually. The high probability of accidents in this line of work can cause many casualties and bring substantial economic loss. Hence, Wall Climbing Robot (WCR), with the ability to maneuver on vertical surfaces are required to perform automatic inspections and cleaning at a significantly faster/safer, and lower cost. In recent years, with the development of mechanical, hydraulic, electronic, and bionic disciplines, many automatic devices have emerged that can climb walls; however, no significant work on wall climbing robots is being done in Pakistan leaving us with no choice other than to import such robots or continue the existing practice of endangering human lives to perform such tasks. Therefore, a significant amount of research is needed in this field.

1.1 Research Objectives

Boilers are widely used in fertilizer and other production industries. When operated for a certain period, there are various kinds of sludge deposits. In addition to that, the thickness of walls is also affected. Regular cleaning and maintenance are performed for these boilers to work efficiently but it is highly costly. With fuel supply dominating nearly 80% of operational costs, maintaining a high level of efficiency is important to annual savings. Boiler Cleaning is either done by robots or manually, that involves high risk and casualties. A normal Boiler Cleaning operation may take up to 2 weeks to perform. Hence, this project, i.e., a wall-climbing robot, provides locally available solutions to industrial and agriculture sectors, who are looking for cheaper and efficient ways of cleaning and maintaining their boilers. This project aims at developing a robot that can maneuver on walls and ceilings with high reliability while carrying a certain payload. Following are the focus of this project:

- Cost-efficiency: The design and manufacturing expense of the robot is kept so that it is lower than the other solutions available in the market.
- Portable: It can be moved around. No large labor is required for carrying from one place to another within the factory or plant.
- Easy to deploy: Robot is designed so that it is easy to deploy, and the cleaning and inspection operations are performed with minimum human intervention.
- Locally available solution

1.2 Deliverables

The project aims at developing a wall climbing robot to maneuver boiler walls and perform the cleaning and inspection operations. Keeping in view the application and scope of this project, defined below are the project deliverables:

1. Climb on vertical water walls made of steel, mimicking the inside of a boiler and cover the complete surface area.
2. Inspection of leakages on vertical steel walls.
3. Clean sludge deposits on vertical steel walls.

1.3 Scope and Limitations of the Project

The project and research are aimed at developing a solution that could be employed for cleaning and inspecting industrial boilers. The application is too advanced and hence not covered altogether in this study. However, proof of methodology and a prototype is presented on which experiments are performed in the most suited environment. As mentioned above in the deliverables This robot is capable of being scaled up or down depending on the application, i.e., certain modification might be required for a different size of a boiler, or a boiler wall made with a non-traditional material.

1.4 Thesis Structure

Chapter 1- Introduction: This chapter provides a brief introduction to the project. It summarizes the project deliverables, scope, and objective of the study. It also gives a rapid insight into the methods implemented for the development and design stages.

Chapter 2- Background and Literature Review: This section has two parts. The first one consists of the research and development stages of wall climbing robots as well as the technology used for the application. in second part wall climbing robots, their applications are elaborated. There is also an extensive review on adsorption and locomotion techniques of wall-climbing robots.

Chapter3- Methodology: This chapter includes the design as well as the selection and integration of key components. It includes the Cad design and circuit design stages of the robot. Also, the robot control through programing on microcontroller.

Chapter4- Results: In chapter 4 various analyses are performed and are used to derive results. These are incorporated in the design modification stages of the project.

Chapter 5- Conclusion and future work: The study enabled us to derive various results through series of experiments, this section covers those results.

CHAPTER 2 – BACKGROUND AND LITERATURE REVIEW

2.1 Background

Humankind has always found ways to make their job easier and less time-consuming. As a result, every machine and tool are the outcome of their eagerness towards simplicity. Vertical wall work has always been challenging and life taking, many people around the globe have done their part towards the development of wall climbing robots. The 1960s and 1970s saw the development of the first wall climbing robots. These robots were primarily created for inspection and maintenance jobs in the nuclear industry and employed suction cups and magnets for adherence.

In the following decades (1980s-1990s), slow but noticeable work was done. Robots that could scale walls (second generation), were improved in terms of mobility and navigation. These robots were able to climb on different surfaces and move through challenging set ups by using locomotion devices like wheels, tracks, and legs.

Wall climbing robots of the third generation, developed between the 2000s and the present, have improved sensing and control capabilities since these robots are equipped with sophisticated sensor systems.

In different industrial environments, wall climbing robots are already capable of carrying out a variety of activities, such as inspection, cleaning, and maintenance. Robots that can scale walls are employed in a variety of fields, such as the power generating sector to examine and repair boilers, the construction sector to inspect and maintain buildings and bridges, and the transportation sector to inspect and maintain pipelines and tunnels.

Although wall climbing robot technology has come a long way, there are still some research gaps that need to be filled. One such area of need is the creation of stronger adhesion mechanisms that can function well in a variety of settings and surfaces. The creation of more sophisticated sensing and control technologies and of more robust and reliable adhesion mechanisms that can perform effectively on a wide range of surfaces and environments. Development of more advanced sensing and control systems is necessary, that can enable robots to perform tasks more accurately and efficiently.

2.2 Applications of Wall-Climbing Robot

Wall-Climbing robots or simply climbing robots are employed in various fields today. If implemented the right way, WCRs benefit in countless ways. The structure/geometry of these robots varies depending on the application.

2.2.1 Cleaning

Wall Climbing Robots (WCRs) are widely used for cleaning purposes [1]. In China, an auto-climbing robot has been designed which is used for cleaning the spherical surface of their National Grand Theatre [29]. Wall climbing robots can also be used for cleaning underwater structures; a robot has been developed for this purpose that uses a flexible crawling mechanism [30]. Furthermore, for cleaning glass walls of high-rise buildings, a robot named Sky-cleaner was developed in 2004 [31]. WCRs have also been used to remove ship rust with the help of high-pressure water jet system [32]. A WCR developed by Ocean Robotics is shown in Figure *1*, which is used for cleaning hulls of ships, underwater.

Figure 1: Underwater Hull Cleaning robot made by Ocean Robotics

2.2.2 Inspection and Testing

Inspection robots are used for non-destructive testing, structural health monitoring and surveillance in hazardous environments [3], [4]. They have been utilized for inspection of defects in different structures. An autonomous WCR was designed in 2006, which can climb oil storage tanks externally and perform inspection using ultrasonic sensors [22]. Moreover, to inspect towers for wind power generators a gecko feature based WCR was built [23]. Robots have also been developed for the inspection of large concrete surfaces such as dams and bridge pylons [24]. Furthermore, such robots can be used to detect defects such as cracks in reservoir tanks and pipelines [25]. Moreover, wall-climbing robots can be used in nuclear power stations for inspection of welds in the main rector cooling gas ducts [26]. Such robots are also being used in aircraft structure inspection. A pantograph-type structural WCR was developed, which can move and inspect in narrow spaces such as sewer pipes [28]. A company, IRISNDT, has developed WCRs for remote inspection in confined spaces.

Figure 2: Remote inspection with robotic systems inspection by IRISNDT

2.2.3 Construction and Maintenance

Machines have been used in construction of large buildings for some time now. Recently people are incorporating robots in construction of huge structures as well as painting high-rise walls of buildings. Such robots are also being used in painting large cargo ships, which would be a highly tedious and difficult job without these robots. A company HausBots along with researchers from University of Warwick have developed a Wall Climbing Robot to paint houses and buildings (Figure 3). University of Stuttgart graduate Maria Yablonina has developed mini wall climbing robot that can be used to create structures using carbon-fiber, paving way to a whole new era of construction that is cheap, fast and can create structures that would otherwise be impossible to build.

Figure 3: WCR by Houseboats painting wall of a Home

2.2.4 Security

WCRs are now being used for security and surveillance, since they can be used where human access is difficult or dangerous. Xiao and Sadegh have developed A City-Climber robot that can be used in urban environments for search and rescue, weapon or tool delivery, inspection, and reconnaissance purposes [33]. Moreover, a wall-climbing robot for anti-terrorist field was developed with six legs and a low-noise vacuum adhesion mechanism [34]. Furthermore, Stanford University has developed a gecko-inspired lizard; United States Department of Defense has funded the project so that these robots can be dispatched as spies to an enemy nation.

2.3. Wall Climbing Robot Techniques

All climbing robots are designed to work over vertical surfaces or ceilings for performing various tasks with high maneuverability and less effort. The base for developing such robots is to study critical technologies to achieve stable motion and reliable adhesion. Currently, in industries, there are four major locomotive methods being used that are: wheel-climbing, crawler-based, leg-footed, and hybrid mechanism (shown in Figure *4*). There are also four mainstream adhesion techniques that are: negative pressure adsorption, magnetic adsorption, bionic adsorption, and electrostatic adsorption (shown in Figure *5*). All these techniques are further discussed below.

2.3.1 Locomotion Techniques

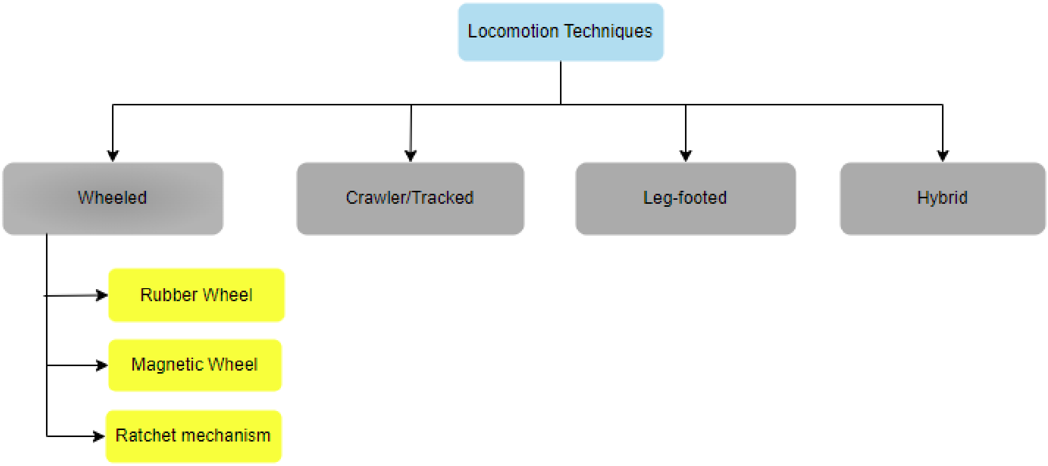


Figure 4: Locomotion Techniques For WCR

Following locomotion techniques are being implemented in Wall-Climbing Robots. Witch method to use depends on the application of the robot. Wheeled robots are best suited for walls that are flat or don’t have much variation in shape. While leg-footed robots are used when the path consists of significant obstacles that are not overcome by wheeled robots.

2.3.1.1 Wheeled Wall-Climbing Robot

As the name suggests, wheels are used for motion in this method. Wheels provide characteristics of flexible turning and fast-moving speed. The robot mainly moves with two or more wheels. The two-wheeled robot is not stable enough when braking and moving at low speed. The three-wheeled robot divides into two types: front-drive and rear-drive, with steady travel and flexible steering. A four-wheel device has a more robust bearing capacity and sufficient driving force.

The six-wheel walking mechanism is mostly used in wall-climbing robots with magnetic adsorption.

There are three main types of wheel mechanism:

- Rubber-wheel: It has a high friction coefficient and is lightweight making it easy to climb.
- Magnetic wheel: The wheel has strong adhesion, and it has a relatively simple structure. It is primarily used in magnetically attracted wall-climbing machines.
- Ratchet mechanisms: There are two main types of ratchets used in wall-climbing robots. First is a ratchet with a bionic viscous adsorbent material that has good adhesion properties and improves the climbing ability. The other is a ratchet mechanism with thorns; designed with reference to the claw thorns of insects or animals.

2.3.1.2 Crawler Wall-Climbing Robot

This method uses crawlers for movement just like tanks. It has more stable movement and rotation since the contact area between the crawler and the wall surface is large, and friction force is significant. This locomotion method is best suited to rough and uneven terrains with obstacles because of large contact surface. They also work better than other methods in soft and slippery terrains. However, they are slow in speed and consume more energy than wheeled robots. Seoul University in South Korea has developed a crawler WCR that has a suction cup installed on each crawler plate and mechanical valves are used to control these suction cups to achieve continuous movement [35]. The WCR developed by Xu and Ma, for labelling scale of oil tanks volume, has permanent magnets installed on the crawler [36]. Carnegie Mellon University in the United States has developed an electromagnetic adsorption using robot, which is equipped with redundant crawlers at the front and rear of the robot, that assist the robot in crossing obstacles [37].

2.3.1.3 Leg-foot Wall-Climbing Robot

This method mimics legged animals for movement. It only needs discrete points to touch the ground, which is more adaptable than other methods, and causes negligible damage to the environment, however it is slow compared to the other methods. Some major WCRs developed using this method are mentioned here. Vanderbilt University in Nashville, Tennessee has designed The Robin Robot that connects two vacuum suction devices through a 4-degree-of-freedom hinge mechanism to walk on the wall and move from the horizontal ground to the vertical wall [38]. Stanford University, California has developed Sticky Bot Robot which uses a force control strategy that allows four legs of the robot to maintain a sizeable contact area with the wall so that the adhesion force can support the robot on smooth glass ceramic tiles and plastic plates [39]. Carnegie Mellon University in Pittsburgh, Pennsylvania has developed The Gecko-Bot Robot from a kinematic structure similar to a gecko with an active tail wing added to improve the steering flexibility and stability [40].

2.3.1.4 Hybrid Wall-Climbing Robot

This method joins two or more of the above-mentioned methods together for locomotion. The three types of Hybrid WCRs are; leg-wheel, leg-track and leg-wheel-track type. This method is best suited where the robot needs to be environment specific. In 2008, Fu, Li and Wang designed a prototype of a wheel-leg hybrid mobile robot that can move on both ground and wall surfaces for rescue, inspection, and surveillance purposes. It has a three-wheeled locomotion mechanism inside a big suction cup, and a mechanical leg with 3 DOF. A Leg-wheel WCR was developed by Liu and Sun in 2013; the robot utilizes bio-inspired spine feet and can move in both upward and downward directions.

2.3.2 Adhesion Techniques

Wall-climbing Robots use different adhesion methods to climb up the walls of high-rise buildings, and large structures. These methods are listed in Figure 5. What method to choose greatly depends on the scope and application of the WCR.

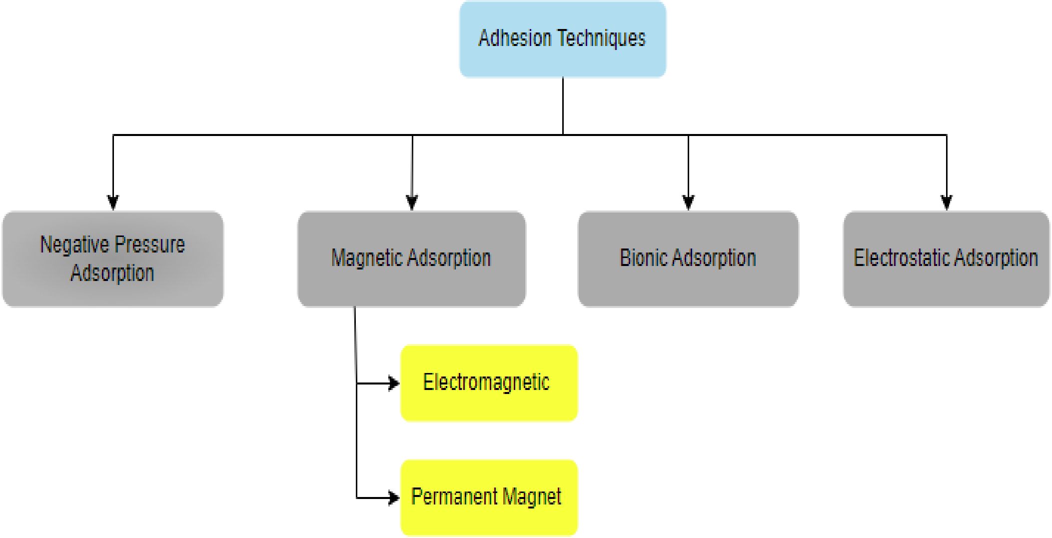


Figure 5: Adhesion Techniques for WCR

2.3.2.1 Negative Pressure Adsorption

When the pressure in a specific area is lower than atmospheric pressure, it is known as negative pressure. The relatively high-pressure atmosphere flows to the negative pressure area, generating a strong force. In negative pressure adsorption, suction cups are used which rely on this phenomenon to squeeze the robot against the wall (Figure 6). Guangzhou University, China has designed a cable-climbing robot using negative pressure adsorption, to inspect broken cables on cable-stayed bridges [8]. Jilin University, Changchun, China designed a project for the optimization of wall-climbing robot impeller by genetic algorithm based on computational fluid dynamics and kriging model [9].

Figure 6: Robot Climbing using suction cups

2.3.2.2 Magnetic Adsorption

Magnetic adsorption method uses magnets to climb on walls. This method is further divided into two sub-types: electromagnetic adsorption and permanent magnet adsorption.

Electromagnetic Adsorption

Electromagnetic adsorption method is based on the principle of electromagnets. A magnetic force is generated by energizing the coil to adsorb on the surface of magnetic metal. The magnetism is easy to control, but the adhesion is weaker as compared to permanent magnets. Jilin University, China has developed a wall climbing robot using electromagnetic adsorption technique [10].

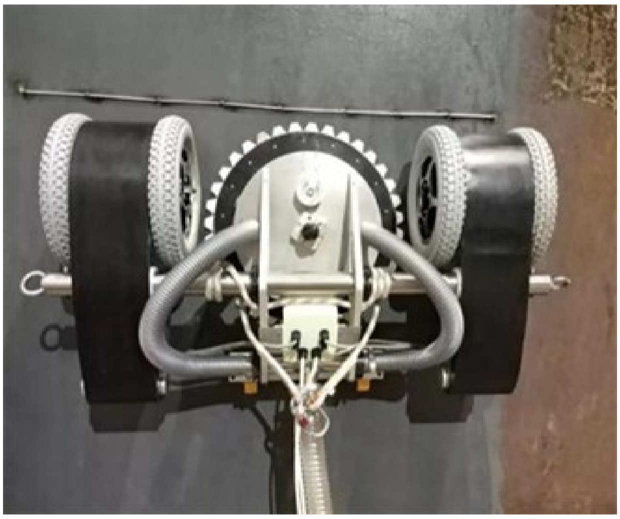


Figure 7: Electromagnetic Adsorption

Permanent Magnet Adsorption

The wall-climbing robot with permanent magnet adsorption is based on magnetic force of the permanent magnet (Figure 8). The adsorption capacity is strong and stable, and the magnetic force can be adjusted according to the distance between the magnet and the wall. However, separating the robot from the wall is not very simple. A WCR with Shape-Adaptive Magnetic Adhesion Mechanism has been designed by Massachusetts Institute of Technology [11]. Al-Ayen University in Iraq has designed a magnetic–type Climbing Wheeled Mobile Robot for Engineering Education. This climbing system is intended to be used for educational and research purposes [12].

Figure 8: WCR using permanent magnets

2.3.2.3 Electrostatic Adsorption

The electrostatic adsorption technique is based on the phenomenon of electrostatic induction. The object without static electricity that is close to the object with static electricity will accumulate charges of opposite polarity to the charge carried by the charged object. Because the opposite charges attract each other, it will show the phenomenon of “electrostatic adsorption”. Due to increasing research on electrostatic adsorption materials and technologies, its application in wall climbing robots is increasing. A crawler wall-climbing robot based on an electrostatic adsorption mechanism robot can successfully achieve linear motion. The downside is that the robot can only achieve steering movements on glass surfaces with an inclination angle of about 30°. BeiHang University, Beijing, China has designed a wall climbing robot based on electrostatic adhesion technology.

2.3.2.4 Bionic Adsorption

Biologically inspired engineering is a flourishing field of modern scientific research. With developments in this field, wall-climbing robots have a wide range of practical application potential. The biomimetic adsorption structure is mainly based on imitating the principle of adhesion of biological feet in nature. It mainly includes the attachment method based on claws and thorns or the adhesion method that generates van der Waals force between the microstructure and the contact object. Inspired by geckos, many scholars have studied adsorption materials to simulate the tendon tissue and skin of gecko's toes. They simulated the adsorption process of geckos by the van der Waals forces generated by close contact with objects, on the micrometer and sub-micrometer scales. Tongji University, Shanghai, China have developed a WCR that uses wet adhesion pads, inspired by arthropods like stick insects.

CHAPTER 3 - METHODOLOGY

The major systems of a wall climbing robot, locomotion, adhesion, motion control, cleaning, and inspection mechanisms. We conducted an extensive research and literature review on methods and techniques that are best suited to our robot. For the adhesion methodology, permanent magnets are used and for locomotion, wheels are used.

To develop an indigenous wall-climbing robot, using permanent magnetic wheels, the following methodology is used: CAD models of the robot are designed and analyzed such that they can ensure a secure and stable grip while moving on vertical walls. Moreover, an electronic circuit and its PCB is designed that consists of a power supply module, motor control subsystem, control unit, and cleaning and inspection mechanism. For cleaning, the WCR is fitted with a water jet system, which is used to remove sludge deposits. Moreover, for the inspection of boiler surfaces the WCR is equipped with a high-resolution camera. Furthermore, mathematical modelling is done for the proposed design for detecting parameters such as number of magnets and torque required, and programming is performed to integrate and control all these components together. This chapter covers these fragments in detail below.

3.1 Hardware Components

When deciding on which components to use, market availability and financial restrictions prevented us from getting one that best suits our design requirements. However, all the components used in our design were able to provide us with desired results. Figure *9* shows the major components used and the command flow. The following are the details of all the equipment used in this project.

The electronic circuitry of the wall climbing robot employs a power supply module to convert 220V AC to a regulated 12V DC, eliminating the need for additional DC batteries. The motor control subsystem, driven by the ZK-5AD motor driver, provides precise control over the two 12V DC motors. The Arduino Nano microcontroller acts as the control unit, powered by a buck converter, and controls the motor subsystem while generating PWM signals for the solenoid-controlled valve within the cleaning mechanism. This comprehensive circuitry design ensures efficient operation of the wall climbing robot, optimizing its performance for vertical wall traversal while reducing overall weight. The electronic circuitry of the wall climbing robot consists of a power supply module, motor control subsystem, control unit, and cleaning mechanism. This section provides a detailed technical description of the components and their functionality.

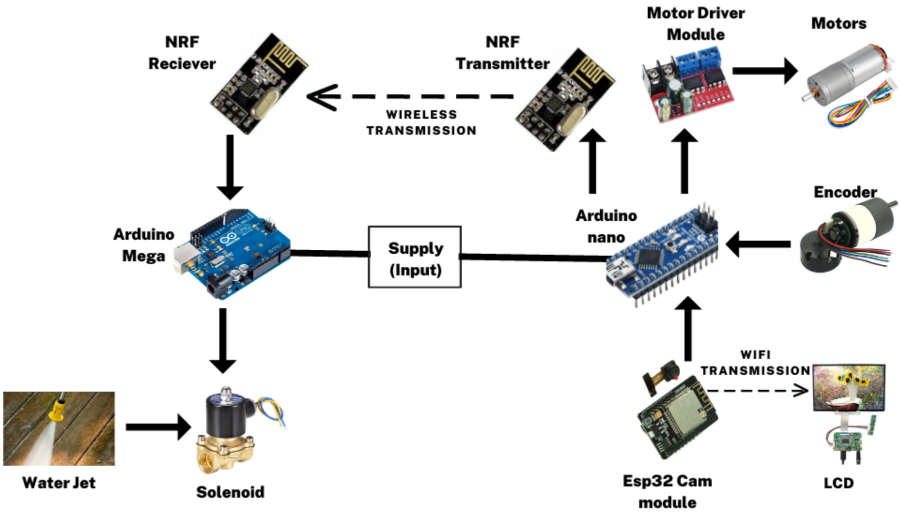


Figure 9: Functional Chart showing the Command Flow

3.1.1 Microcontrollers

Arduino is an open-source electronics platform that can be used to program applications that are not large scale. Due to its easy-to-use hardware and software, it provides easy debugging through Arduino IDE. The programming language used in the Arduino platform is a variant of the Wiring language, which is based on C/C++. The language includes several functions and libraries that simplify the programming of the microcontroller and the connected devices.

1. Arduino Mega: In addition to motion control, the cleaning system of the robot, that consists of a water jet, is controlled by Arduino Mega. This microcontroller receives a signal from Arduino nano and generates pulse-width modulation (PWM) signals for the cleaning

mechanism's solenoid control. This this transmission of signals between the micro-controllers is done through NRF transceiver.

Figure 10: Arduino Mega

2. Arduino Nano: It has input pins that can take sensor values to further process them in its IDE. The results of the program can be carried out via the output pins on the Arduino Nano. In this project, Arduino connects Esp32 camera module to an outer source such as a display/monitor. The purpose is to direct the captured footage for further processing. The microcontroller also receives input from the motor's encoders, which is used to control the speed and position of the robot. Additionally, it regulates the flow of water jet through the nozzle by toggling the solenoid valve on and off, which is connected between the pump and the water nozzle. The microcontroller is powered by a buck converter that steps down the 12V DC supply from the power supply module to a stable 5V DC, ensuring proper functioning of the microcontroller. The Arduino Nano receives input signals from various sensors, processes them, and executes control algorithms to drive the motor control subsystem.

Figure 11: Arduino Nano

3.1.2 Motor Drivers

The following 2 motor drivers are used in the robot control circuit, for controlling the motion of robot and for driving water jet.

1. ZK5AD: Is a dual motor driver or single stepper motor driver based on TA6586 chip. It is a high power, small size, low power consumption and simple operation dual driver that supports independent control for 2 motors. This module enables us to control the speed and direction of motors, thus controlling the movement of robots. It has an H-bridge circuit that controls the current flow through the motor, input pins for controlling the motor's direction and speed, and an external power supply that is connected to a microcontroller i.e., Arduino Nano. With a peak current of up to 5A, it drives motors ranging voltage between 3 volts to 14 volts. The speed of actuator is varied by setting Pulse Width Modulation (PWM) through a controller and giving a signal to H-bridge to drive DC motor according to the desired speed and duty cycle.
2. L298N: Yet another motor driver. It is a dual motor control circuit. L298N has a peak current of 2A, this module is used to control the cleaning mechanism (solenoid).

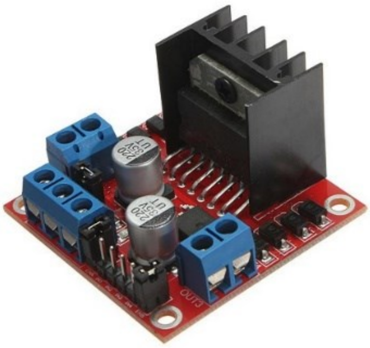


Figure 12: Motor Driver Module

Figure 13: ZK5AD, motor driver

3.1.3 Esp32 Camera Module

For inspecting the walls of boiler for any leakages and damage, a live footage should be obtained. This is done by using esp32 camera module (Figure *15*), that collects the video footage of the boiler and sends it back to the display screen that is wirelessly connected to it. Obtaining this footage is only the first step, achieved within the scope of this project. This footage can be integrated into various AI technologies that use neural networks to analyze and design various results regarding the condition of the plant/boiler. This, however, was not covered within the scope of this project.

3.1.4 Motors

This project utilizes 12V Brushless Direct Current (BLDC) motors equipped with encoder feedback. The motors used are fit0186, as shown in Figure 14, which are 12v motors with a speed of 250 revolutions per minute (rpm), stall torque of 1.76 Nm and an encoder count of 700 counts per revolution. The encoders, mounted at the end of each motor, provide connection between motors and the rest of the system, preventing complete isolation of motors. These encoders provide feedback on parameters such as rotational speed and direction. This data can be utilized to program the system to minimize unbalanced movements and mitigate shocks caused by irregular surfaces or obstacles.

Figure 14: Encoder motor to control position and speed

Figure 15: Esp32 Camera

The motor control subsystem facilitates the operation of the wall climbing robot's two 12V DC motors. It incorporates the ZK-5AD motor driver, which receives power from the power supply module. The ZK-5AD motor driver interfaces with the motors and provides control signals, enabling precise control over motor speed, direction, and rotation.

3.1.5 Power Supply Module

The power supply module is responsible for delivering the appropriate voltage to the various components of the robot. It comprises an AC to DC converter that converts the 220V AC input from a plugged board to a regulated 12V DC output. This converted 12V DC power is utilized throughout the system, eliminating the need for additional DC batteries, and reducing overall weight.

3.1.6 Water Jet & Solenoid Valve

To ensure the efficiency of a boiler, regular cleaning and maintenance is required. With time, boilers can accumulate various sludge deposits that render their proper working. Hence, this WCR is specifically designed to clean walls of the boilers. Water is supplied to the robot through a pipe that is connected to a motor pump that can provide 100 MPa pressure and a flowrate of 330 L/h. The pipe is further connected to a solenoid and nozzle system, which allows effective cleaning of the wall. The specific mechanism employed may vary depending on the type of boiler surface and the nature of the deposits.

Figure 16: Water pump and nozzle system for cleaning mechanism

The cleaning mechanism implemented on the robot incorporates a solenoid-controlled valve. The valve's opening and closing is regulated through high and low signal generated by the Arduino Nano microcontroller. This allows precise control of the solenoid, facilitating the required fluid flow adjustments based on the robot's position and cleaning requirements.

Figure 17: Solenoid Valve to control water flow

3.1.8 NRF24L01 Transceiver

In this project NRF24L01 is used for communication between two Arduino boards. Arduino Nano is mounted on the robot, which is used for controlling motors and camera while an Arduino mega is used to control solenoid valve connected to the water pump to control the water flow. Hence, wireless communication between the two Arduino boards is required for efficient working of the complete system. For this purpose, two NRF24L01 are used, one relates to the Arduino nano which acts as a transmitter, it sends signal to the other Arduino about whether to turn the solenoid on or off. The second NRF24L01 is connected to the Arduino mega that acts as a receiver, when a signal is received the Arduino decides if the solenoid needs to be turned on/off.

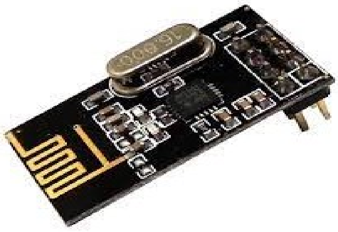


Figure 18: NRF24L01

3.2 CAD Modelling

The process of 3D modeling plays a pivotal role in this thesis, as it serves as the foundation for the design and development of the wall climbing robot for cleaning and inspection of boilers. Through the utilization of SolidWorks, a powerful CAD (Computer-Aided Design) software, the modeling phase enables the creation of a digital representation of the robot and its components in a virtual environment. This step holds significant importance as it allows for the visualization, analysis, and refinement of the robot's design before the physical construction begins.

The 3D modeling feature in SolidWorks provides a comprehensive set of tools and functionalities that aid in accurately depicting the robot's structure, dimensions, and mechanisms. It allows for the creation of intricate geometries, precise measurements, and realistic simulations, enabling the exploration of various design iterations and ensuring optimal performance.

During the modeling process, attention is given to the interplay of different parts, ensuring their compatibility, assembly, and functionality. The intricate details of the robot's components, such as motor mounts, cleaning mechanism, and camera module integration, are meticulously crafted and validated through the modeling stage. This comprehensive approach aids in identifying potential design flaws, optimizing the robot's performance, and ensuring safety.

Moreover, 3D modeling aids in the identification of manufacturing requirements, material selection, and cost estimation. It serves as a valuable communication tool, facilitating collaboration with stakeholders and enabling effective visualization of the robot's features and capabilities.

3.2.1 Magnetic Wheels

For this project, a new wheel was designed with magnets placed inside it to provide adhesion for the robot while climbing walls. To minimize weight, a thin aluminum rim was designed and attached to a rubber tire that contains holes for permanent magnets to be fixed inside. Calculations were performed to determine the required number of magnets to hold the robot on the wall without slipping[43]. Additionally, calculations were done to determine the optimal wheel radius that would allow enough magnets to be fitted on one wheel while keeping the motors close to the wall. As a result, a wheel with a radius of 3.5 cm and a rubber thickness of 0.3 cm was produced. Figure *19* below shows the final model of our magnetic wheel.

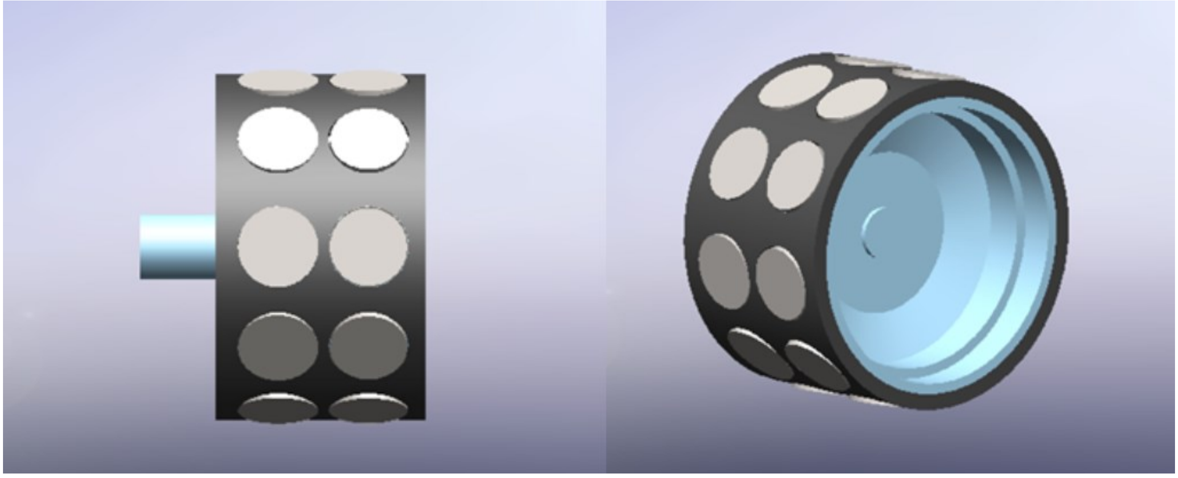


Figure 19: Magnetic Wheel Design

3.2.2 Base Design

A design was initially devised for a base plate capable of accommodating four motors connected to four wheels. The chosen configuration employed a rectangular shape with the motors evenly positioned to maintain a balanced center of gravity and center of rotation. However, to enhance efficiency and reduce weight, the design underwent revisions. Consequently, a new design emerged, featuring only two motors and two wheels.

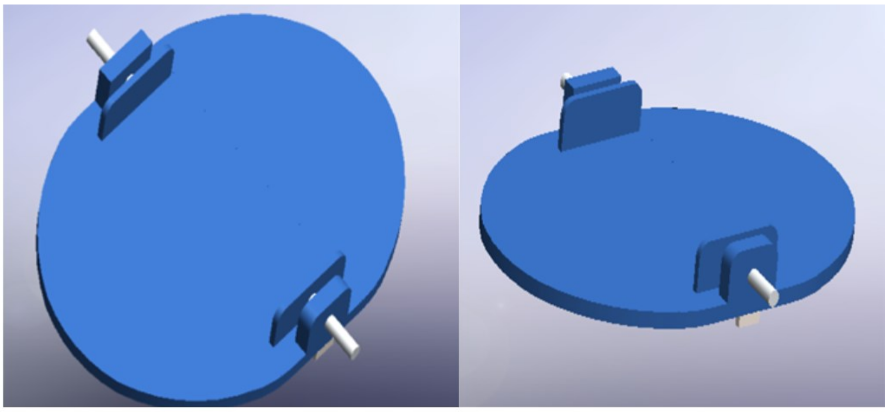


Figure 20: Robot's Base Design

To ensure stability after the reduction in motor count, two ball caster wheels equipped with magnetic balls were introduced to provide additional support. Furthermore, modifications were made to the base shape, incorporating circular edges at the front and rear to stabilize the robot base alongside the caster wheels. The finalized base design can be observed in Figure *20*.

3.2.3 Water Guard

This project aims to clean boiler walls, necessitating the utilization of water-based cleaning methods. Consequently, the use of a water jet becomes essential. However, special attention must be given to protecting the electronic circuits from water exposure. To address this concern, a water-resistant shield is designed and mounted over the robot base. This shield effectively safeguards the base against water spillage and potential damage. The model of the water-guard shield is depicted below in Figure *21*.

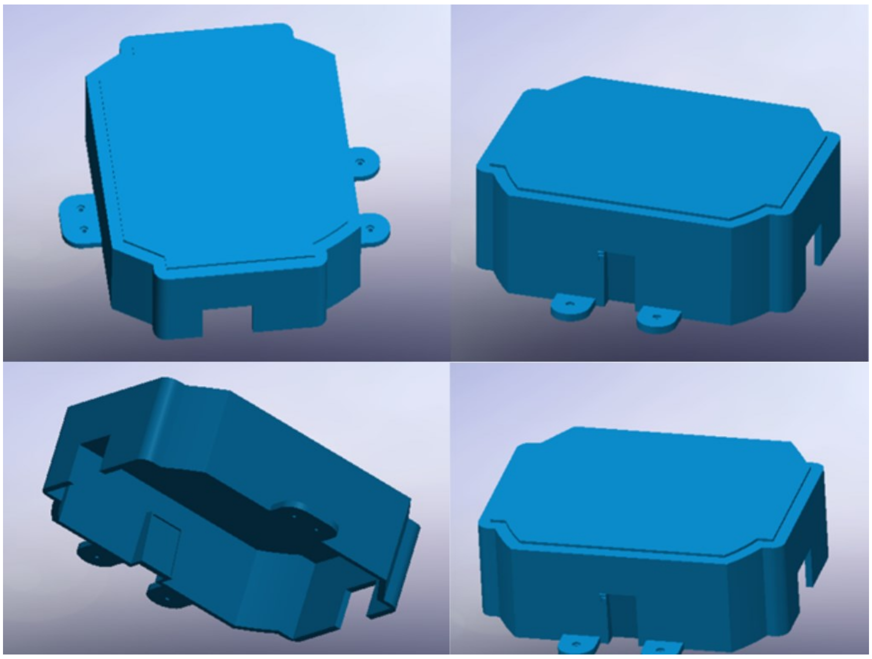


Figure 21: Water Protective Case for Robot

3.2.4 Motors

Solid works model of motors used in this project is as shown below in Figure 22, the working and function of these motors is explained above in section 3.1.4.

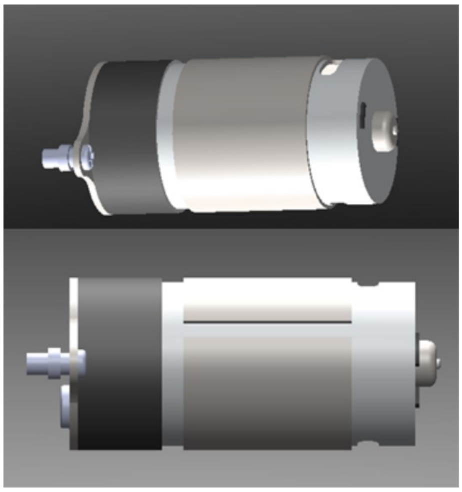


Figure 22: 3D model of motor used in WCR

3.2.5 Water Jet

The water jet mechanism plays a crucial role in the cleaning process of the wall climbing robot. It is designed to effectively remove dirt and debris from the boiler walls through the projection of a high-pressure water stream. The modeling of the water jet mechanism in SolidWorks allows for a detailed representation and analysis of its components and functionality.

The water jet mechanism typically consists of a water pump, a reservoir, a nozzle, and associated tubing. The pump draws water from the reservoir and delivers it under pressure to the nozzle, which emits a focused jet of water onto the boiler walls. There are various types of nozzles which are suitable for different purposes such as flat fan nozzle, full cone nozzle and hollow cone nozzle. Among these, the flat fan nozzle provides a rectangular shaped output of water, which covers more surface area while reducing the amount of water splash towards the robot. Hence, the flat fan type of nozzle is selected for this project. Figure 23 below shows the model of the nozzle designed to meet water jet specifications required for this project.

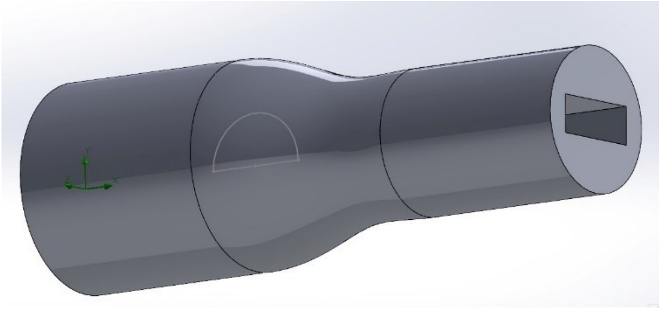


Figure 23: Nozzle Design for Water Jet

3.2.6 Robot Assembly

The assembly of the wall climbing robot in SolidWorks marks a crucial step in the development process, as it brings together all the individually modeled parts into a cohesive and functional unit. This assembly process involves integrating components such as two wheels, two motors, a water guard, and a base to create a complete robot structure capable of climbing and cleaning the boiler walls.

The two wheels, meticulously designed and modeled, provide the robot with traction and maneuverability during its climbing operations. These wheels are coupled with the corresponding motors, which drive their rotation and enable the robot's movement along the vertical surface of the boiler. The precise integration of the motors and wheels is crucial to ensure a smooth and stable climbing motion.

The water guard, another essential component, is designed to protect the robot's sensitive electronic and mechanical parts from water damage during the cleaning process. This component is strategically positioned to shield critical areas and prevent water ingress, ensuring the longevity and reliability of the robot's operation.

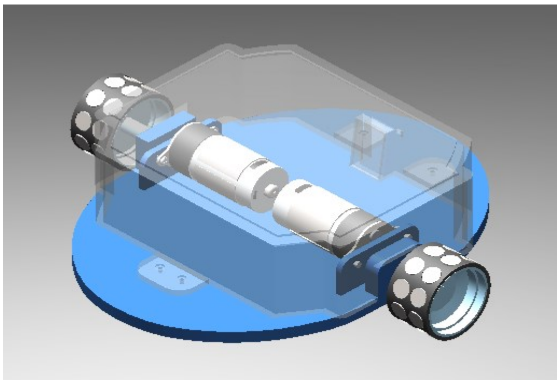


Figure 24: Robot base Assembly

Finally, the base serves as the foundation and structural support for the entire robot assembly. It provides stability and rigidity, allowing the robot to withstand the forces and stresses encountered while climbing and cleaning the boiler walls. The base is carefully designed and modeled to accommodate all the necessary components, ensuring proper alignment and functionality.

By assembling these modeled parts in SolidWorks, we create a holistic representation of the WCR, ready for further analysis, simulation, and visualization, shown in Figure 24. This assembly process ensures the seamless integration and interaction of the various components, enabling a comprehensive understanding of the robot's overall structure, functionality, and performance.

3.3 Mathematical Models

Water pump used for this project has specifications of pressure 100 bars and flowrate (q) of 0.09 kg/s. Diameter of the nozzle is kept as 6.5mm which gives an area (A) of 0.000033187m^2.

To calculate velocity of the water jet:

$$v = \frac{q}{\rho A} = 2.7m/s$$

Force due to water jet:

$$F_w = v \times q = 0.31N$$

Keeping nozzle of the water jet at an angle of 50 degrees:

$$\mathrm{F_{wdown}} = \mathrm{F_w \sin 50} = 0.24\mathrm{N}$$

To prevent slippage while the robot is stationary on the wall friction provided by both the wheels should be greater than weight of the robot[2]:

$$2\mathrm{F_r} \geq \mathrm{mg}$$

$$\mathrm{F_r} = \mu \mathrm{N}$$

$$\mathrm{n.F_m} = 2\mathrm{N}$$

$$(2\mu \mathrm{n.F_m})/2 \geq \mathrm{mg}$$

Where,

$\mathrm{F_r}$ = Friction Force

$\mathrm{F_m}$ = Magnetic Force

Taking wet coefficient of friction(μ) of rubber

$$\mu = 0.4$$

$$\mathrm{n.F_m} \geq \frac{\mathrm{mg}}{0.4}$$

The forward force provided by the motor to move upward:

$$\mathrm{F} = \frac{2\mathrm{F_r} + \mathrm{mg} + \mathrm{F_w \cos \emptyset}}{2}$$

$$\mathrm{T} = \mathrm{F.r}$$

Radius of wheel (r) = 3.5cm

Table 1: Relation between the distance of robot from surface and force/torque

Sr.	Weight kg	n. F_m N	Distance mm	Force N	n	Force N	T Nm
1.	1	24.5	1	10	3	9.9	0.35
2.	1	24.5	2	5.8	5		
3.	2	49	1	10	5	19.7	0.69
4.	2	49	2	5.8	9		
5.	3	72.5	1	10	8	29.3	1.03
6.	3	72.5	2	5.8	13		
7.	4	97.5	1	10	10	39.2	1.37
8.	4	97.5	2	5.8	17		
9.	5	122.5	1	10	13	49.1	1.72
10.	5	122.5	2	5.8	21		

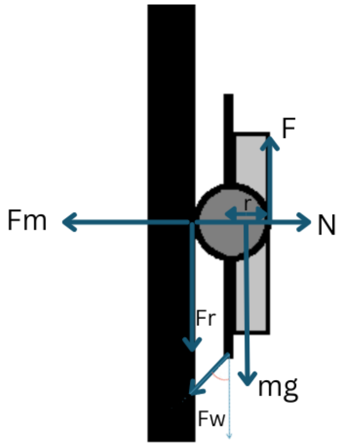


Figure 25: Free body diagram for representation of forces acting on robot

Magnetic force is calculated by varying the weight of the robot between 1kg to 4kg. Moreover, for each weight two forces are calculated by keeping the distance of the [3] magnet from the wall 1mm and 2mm. After calculating the required force and force provided by one magnet, the number of magnets required (n) are calculated. Furthermore, torque is calculated for each different weight. These results are shown in Table 1 below.

3.4 Software Simulations

Robot manufacturing and design consists of various steps that should be performed to get the most accurate results. There are various tools available for performing simulations that help to design and test hardware or other software components of a design. We have used these tools such as Solid works, Proteus, and Ansys in the design phase of the project.

3.4.1 Proteus Simulation and PCB Design

The Arduino microcontroller is the primary controller in the robot system, tasked with receiving and processing data from various sensors, including the ESP32 camera module and encoder motors. It runs on a 16MHz crystal oscillator and has 14 digital I/O pins and six analog input pins. The motor driver module is responsible for driving the two encoder motors that enable the robot to climb the boiler walls. The L298N motor driver module can provide up to 2A per channel, with a total of four channels available, and allows for the bi-directional control of DC motors. The ESP32 camera module integrated into the system provides real-time footage, facilitating the remote monitoring and control of the robot's movements. The camera captures images in VGA resolution and can stream video at up to 30fps. It is made to support Wi-Fi and Bluetooth connectivity, enabling wireless transmission of data to the main controller, although not in scope of this project.

The water jet mechanism plays a vital role in the system, enabling the thorough cleaning of the boiler walls. This mechanism consists of a water pump that draws water from a reservoir and propels it through a nozzle positioned on the robot. Controlled by the microcontroller, the solenoid valve serves as the link between the pump and the nozzle. When the solenoid receives electrical current, it opens, allowing the nozzle to emit a powerful, high-pressure jet of water onto the walls. This process effectively eliminates any accumulated dirt and debris, ensuring a thorough cleaning.

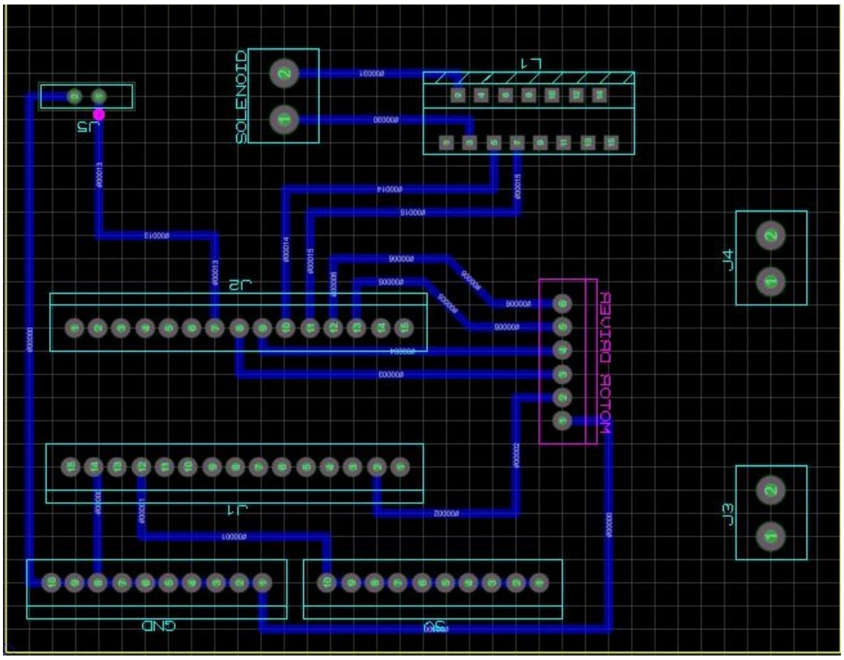


Figure 26: PCB design

The circuit designed in Proteus software facilitates the integration and communication of these components. The connections between the Arduino, motor driver module, ESP32 camera module, and other peripherals are carefully established, ensuring proper signal transmission and control. The circuit design also accounts for power management, implementing voltage regulation and current limiting mechanisms to protect the components and optimize performance. Figure 26 shows the designed PCB to cover the electronic requirements for this project.

3.4.2 Kinematic Model

Kinematic modeling is the use of mathematical formulas and models to represent and describe the motion of an object or system. Analyze the position, velocity, and acceleration of objects without considering the forces that cause their motion. Kinematic models are widely used in various fields such as physics, engineering, robotics, computer graphics and animation.

There are different approaches to kinematic modeling depending on the complexity of the system under analysis. For WCRs system taken as land-based robot with differential wheels, it has three degrees of freedom, longitudinal, lateral and rotation about its vertical axis. The following equations demonstrate the simulation and analyzation in velocity level through forward kinematics.

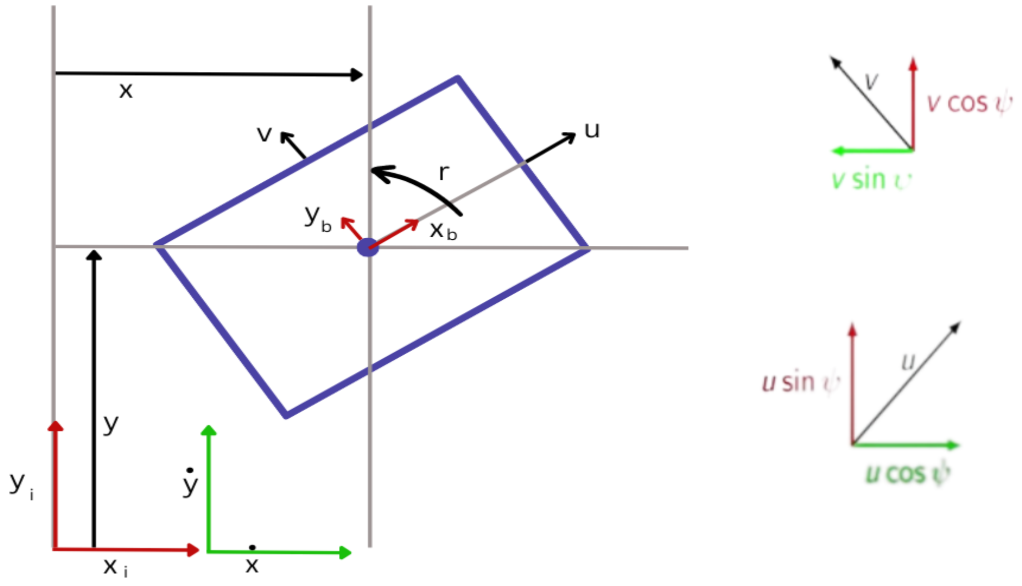


Figure 27: Kinematic model for robot

x: *Forward displacement of the mobile robot w.r.t. I*

y: *Lateral displacement of the mobile robot w.r.t. I*

ψ: *Angular displacement of the mobile robot w.r.t. I*

u: *Forward velocity of the mobile robot w.r.t. B*

v: *Lateral velocity of the mobile robot w.r.t. B*

r: *Angular velocity of the mobile robot w.r.t. B*

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} u\cos\psi - v\sin\psi \\ u\sin\psi + v\cos\psi \\ r \end{bmatrix}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} u\cos\psi - v\sin\psi \\ u\sin\psi + v\cos\psi \\ r \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix}$$

$$\eta' = J(\psi) * \zeta$$

It describes the relation between the velocity input commands (ζ) and the derivatives of generlized coordinates(η').

$$The\ known\ mobile\ robot\ kinematic\ model, as:$$

$$\eta' = J(\psi) * \zeta$$

$$Based\ on\ wheel\ configuration$$

$$\zeta = W * \omega$$

$$(\boldsymbol{\eta'}) = the\ vector\ of\ time\ derivatives\ of\ generalized\ coordinates.$$

$$J(\psi) = the\ Jacobian\ matrix\ which\ maps\ the\ input\ velocity$$

$$commands\ to\ derivatives\ of\ generalized\ coordinates.$$

$$\zeta = the\ vector\ of\ velocity\ input\ commands.$$

$$W = the\ wheel\ input\ or\ configuration\ matrix.$$

$$\omega = the\ vector\ of\ wheel\ angular\ velocities.$$

$$\omega_i = \begin{bmatrix} \frac{1}{a_i} & \frac{1}{a_i} tan\emptyset_i \end{bmatrix} \begin{bmatrix} cos\theta_{Bi} & sin\theta_{Bi} \\ -sin\theta_{Bi} & cos\theta_{Bi} \end{bmatrix} \begin{bmatrix} 1 & 0 & -d_{yi} \\ 0 & 1 & d_{xi} \end{bmatrix}$$

$$\omega_i = Angular\ velocity\ of\ the\ ith\ wheel.$$

$$a_i = Radius\ of\ the\ ith\ wheel.$$

$$\theta_{Bi} = Anglebetweenthevehicleframe(B)tothewheelframe(c_i).$$

$$d_{xi}\ and\ d_{yi}\ are\ the\ position\ coordinates\ of\ c_i\ with\ reference\ to\ B.$$

$$\phi_i = Anglebetweenrolleraxistothex_ciaxis.$$

$$u = Forward\ velocity\ of\ the\ mobile\ robot\ w.r.t. frame\ B.$$

$$v = Lateral\ velocity\ of\ the\ mobile\ robot\ w.r.t. frame\ B.$$

$$r = Angular\ velocity\ of\ the\ mobile\ robot\ w.r.t. frame\ B.$$

$$As\ we\ know\ for\ the\ differential\ wheels:$$

$$d_{x1} = 0\,, d_{y1} = d\,, a_1 = a$$

$$d_{y2} = -d\,, d_{x2} = 0\,, a_2 = a$$

So above equation becomes:

$$\begin{bmatrix} u \\ v \\ r \end{bmatrix} = \zeta = \begin{bmatrix} \frac{a}{2} & \frac{a}{2} \\ 0 & 0 \\ \frac{-\,a}{2d} & \frac{a}{2d} \end{bmatrix} * \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix} = W * \omega$$

$$\Rightarrow \eta' = J(\psi) * W * \omega$$

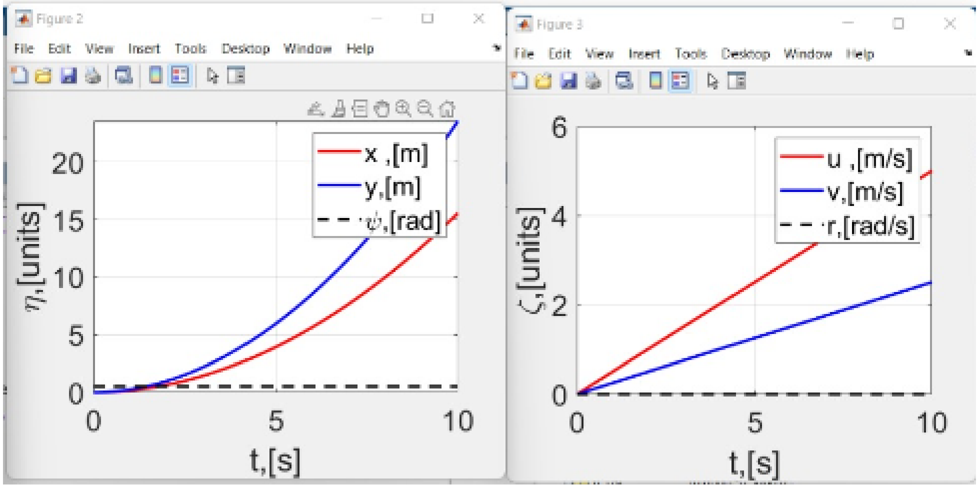


Figure 28: Robot's Movement in MATLAB

This equation is then used to simulate our WCR in MATLAB to simulate the movement of the robot with respect to given angular velocity based on motor rpm, wheel radius and the distance between wheel frame and body frame. MATLAB code is attached as ANNEX for reference.

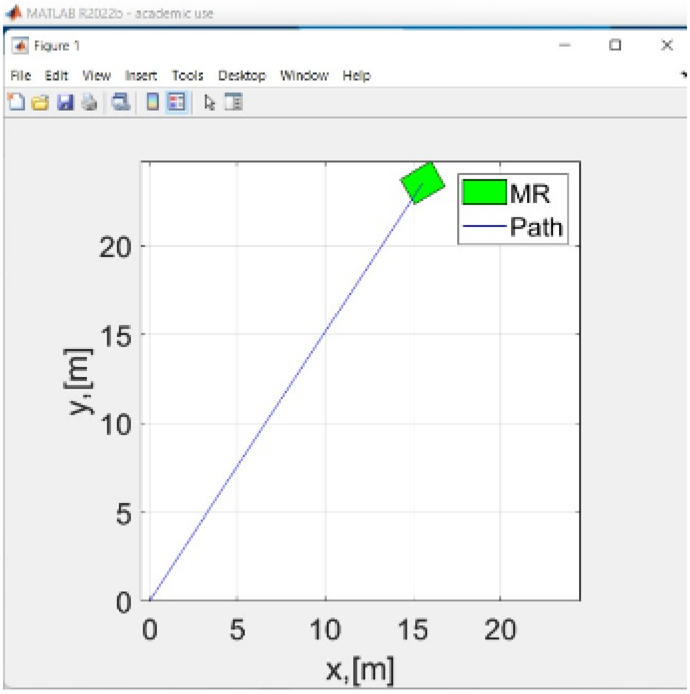


Figure 29: MATLAB Simulation showing robot's Kinematic model

3.4.3 Dynamic Model

Dynamic modelling in context of engineering involves developing a mathematical representation of the robot’s behavior and movement while climbing the vertical walls. This allows us to understand and predict the actions, performance, and stability during climbing process. The dynamic model for this robot will consist of various key aspects such as focusing on the forces and torques acting on it and their effects on its motion this requires the consideration of certain factors as gravity, contact forces and friction between and wall and robot. This also involves articulating equations of motion to describe the acceleration and angular acceleration based on the forces that are being applied dynamic modelling is a great source to design control strategies for the robot.

By Euler’s formula:

$$\frac{d}{dt}\left(\frac{\delta E}{\delta v}\right) - \frac{\delta E}{\delta x} = 0$$

By Lagrange equation

$$L = K.E - P.E$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta v}\right)-\frac{\delta L}{\delta x}=F$$

$$K.E=\frac{1}{2}m\left[\dot{x_c}^2+\dot{y_c}^2\right]$$

$$\dot{x_c}=u-y_{bc}r$$

$$\dot{y_c}=\ v+x_{bc}r$$

$$\dot{x_c}=u-y_{bc}r$$

$$\dot{y_c}=\ v+x_{bc}r$$

Kinetic Energy

$$K.E=\frac{1}{2}m\left[\dot{x_c}^2+\dot{y_c}^2\right]+\frac{1}{2}I_zr^2$$

Potential Energy

$$P.E=mgh$$

$$L=K.E-P.E$$

$$\tau_i=\frac{d}{dt}\,\frac{\delta L}{\delta\dot{q_\iota}}-\frac{\delta L}{\delta q_i}$$

$$L=K.E-P.E=\frac{1}{2}m\left[\dot{x_c}^2+\dot{y_c}^2\right]+\frac{1}{2}I_zr^2+mgh$$

$$=\frac{1}{2}m\left(u^2-2ury_{bc}r+v^2+2vrx_{bc}+r^2\left[x^2{}_{bc}+y^2{}_{bc}\right]\right)+\frac{1}{2}I_zr^2+mgh$$

$$F_x=\frac{d}{dt}\,\frac{\delta L}{\delta u}$$

$$F_y=\frac{d}{dt}\,\frac{\delta L}{\delta v}$$

$$Mz=\frac{d}{dt}\,\frac{\delta L}{\delta r}$$

$$L=\frac{1}{2}m\left(u^2-2ury_{bc}r+v^2+2vrx_{bc}+r^2\left[x^2{}_{bc}+y^2{}_{bc}\right]\right)+\frac{1}{2}I_zr^2$$
$$+mgh$$

$$\frac{\delta L}{\delta u} = mu - mry_{bc}\left[\dot{x_c}^2 + \dot{y_c}^2\right]$$

$$\frac{\delta L}{\delta v} = mv + mrx_{bc}$$

$$\frac{\delta L}{\delta r} = -muy_{bc} + mvx_{bc} + mr\left[\dot{x_c}^2 + \dot{y_c}^2\right] + I_z r$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta u}\right) = m\dot{u} - m\dot{r}y_{bc} - mr\dot{y}_{bc}$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta v}\right) = \ m\dot{v} + m\dot{r}x_{bc} + mr\dot{x}_{bc}$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta r}\right) = -m\dot{u}y_{bc} - mu\dot{y}_{bc} + m\dot{v}x_{bc} + mv\dot{x}_{bc} + m\dot{r}\left[x^2{}_{bc} + y^2{}_{bc}\right]$$
$$+ 2mr[2x_{bc}\dot{x}_{bc} + 2y_{bc}\dot{y}_{bc]+}I_z\dot{r}$$

$$\dot{x_c} = u - y_{bc}r$$

$$\dot{y_c} = \ v + x_{bc}r$$

$$F_x = m(\dot{u} - vr - x_{bc}r^2 - y_{bc}\dot{r})$$

$$F_y = m(\dot{v} + ur - y_{bc}r^2 - x_{bc}\dot{r})$$

$$M_z = I_{cz}\dot{r} + m(x_{bc}[\dot{v} + ur] - y_{bc}[\dot{u} - vr]) + m\dot{r}\left(x^2{}_{bc} + y^2{}_{bc}\right)$$

$$F_x = mac_x$$

$$F_x = m(\dot{u} - vr - x_{bc}r^2 - y_{bc}\dot{r})$$

By Newton Euler Method,

$$F_x = ma_{cx}$$

$$F_x = m(u - vr - \dot{x}_{bc}r^2 - y_{bc}\dot{r})$$

$$F_y = m(v + ur - \dot{y}_{bc}r^2 + x_{bc}\dot{r})$$

$$M_z = I_{cz}\alpha_{cz} - m\alpha_{cz}y_{bc} + m\alpha_{cy}x_{bc})$$

$$M_z = I_{cz}r - m(x_{bc}[\dot{v} + ur] - y_{bc}[\dot{u} - vr\ ]) + m\dot{r}\left({x^2}_{bc} + {y^2}_{bc}\right)$$

$$\begin{bmatrix} m\dot{u} - mvr - mx_{bc}r^2 - my_{bc}\dot{r} \\ m\dot{v} + mur - my_{bc}r^2 + mx_{bc}\dot{r} \\ \left(I_{cz} + m(x_{bc}^2 + y_{bc}^2)\right)\dot{r} + m(x_{bc}[\dot{v} + ur] - y_{bc}[\dot{u} - vr]) \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \\ M_Z \end{bmatrix}$$

$$\begin{bmatrix} m\dot{u} - 0\dot{v} - mx_{bc}r^2 - mvr - my_{bc}\dot{r} \\ 0\dot{u} + m\dot{v} + mur - my_{bc}r^2 + mx_{bc}\dot{r} \\ -my_{bc}\dot{u} + mx_{bc}\dot{v} + \left(I_{cz} + m(x_{bc}^2 + y_{bc}^2)\right)\dot{r} + mx_{bc}ur - my_{bc}vr \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \\ M_Z \end{bmatrix}$$

$$\begin{bmatrix} m & 0 & -my_{bc} \\ 0 & m & mx_{bc} \\ -my_{bc} & mx_{bc} & I_{cz} + m(x_{bc}^2 + y_{bc}^2) \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} -mr(v + x_{bc}r) \\ mr(u - y_{bc}r) \\ mr(x_{bc}u + y + bc\ v) \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \\ M_Z \end{bmatrix}$$

$$\boldsymbol{D}\dot{\boldsymbol{\zeta}} + \boldsymbol{n}(\boldsymbol{\zeta}) = \boldsymbol{\tau}$$

Through combining these characteristics, a dynamic model of a vertical wall-climbing robot simulates its climbing, optimize its performance, and predict its stability. This model could be then used to evaluate the effect of design changes, test different climbing strategies, and identify possible issues or limits before building and positioning the robot physically.

3.4.4 Programming of WCR

The integration of motor control circuit, with inspection and cleaning mechanism is achieved using Arduino nano(microcontroller). Programming being performed in Arduino IDE.

3.4.4.1 Encoder Feedback and PI Control

The robot is programmed using the Arduino IDE. To calculate the velocity, we utilized the motor's encoders. We established a target velocity and compared the calculated velocity with it to identify the error. We then employed Proportional Integral (PI) control to eliminate the error and attain the desired velocity value. The encoders were also used to determine the motor's position, which was used to calculate the distance travelled by the robot. The following calculations demonstrate how the position is determined for a distance travelled of 4 feet:

$$\mathrm{r_{wheel}} = 1.378"$$

$$\mathrm{C} = 2\pi \mathrm{r_{wheel}} = 8.65"$$

$$\text{To cover 4ft wall: 48-9} = \frac{39}{8.65} = 4.5"$$

$$\text{Motor Counts per revolution CPR} = 700$$

$$\text{Encoder position} = 4.5(700) = 3150 \text{ counts}$$

Based on the robot's position, the controller identifies where a turn is required.

3.4.4.2 Wi-Fi Transmission

At the turning point, the solenoid is activated to switch off the water jet until the turn is completed to ensure smooth turning. The motion control circuit is synchronized with the cleaning mechanism. This transmission is performed through the implementation of NRF24L01, Arduino nano is the transmitter micro-controller while Arduino mega is the receiver microcontroller. As soon the motors try to take turn a signal is sent to the NRF Receiver the turns off the water jet through solenoid.

The robot's movement is programmed such that while ascending, the force of the water jet, mounted towards the rear end, assists in moving against gravity. Conversely, while descending, the force applies an upward force to prevent the robot from descending rapidly. Figure 30 below displays the flowchart of the code. Refer to ANNEX for Arduino code.

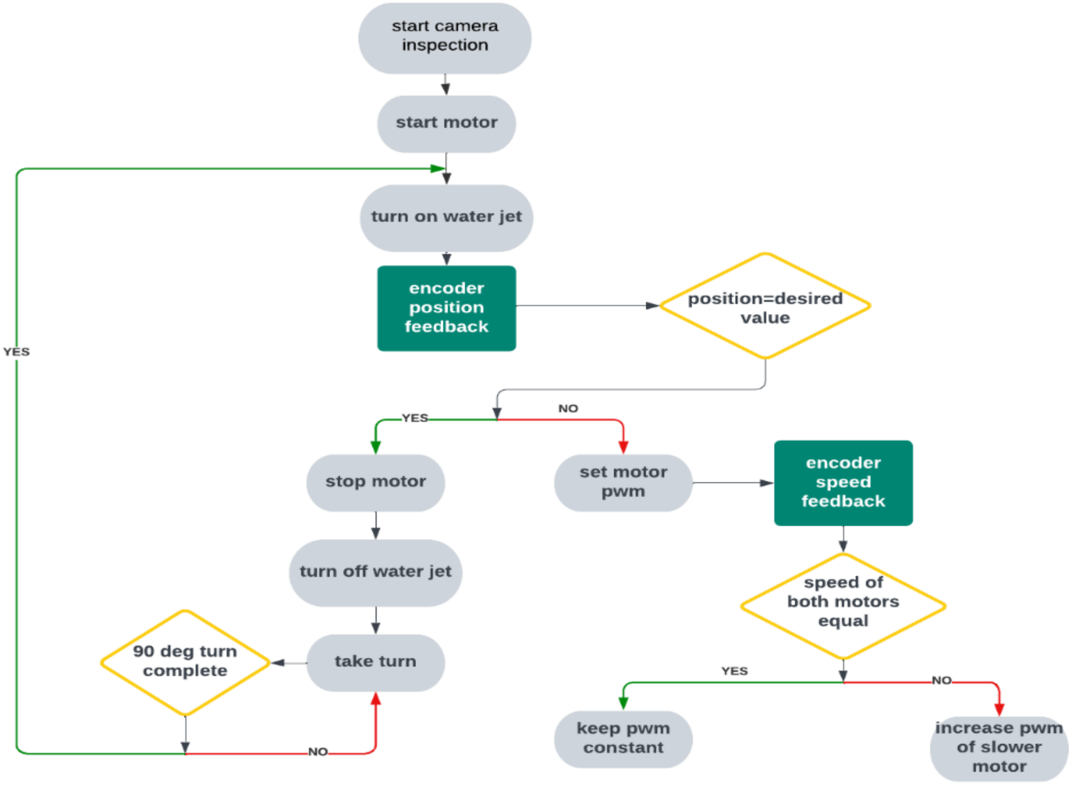


Figure 30: Flowchart showing flow of command for controlling micro-controller

3.5 Robot Fabrication

3.5.1 Material Selection

To fabricate the model of our base three materials were considered that are as follows.

- **Aluminum:** Properties of aluminum vary depending on the type of alloy however typically it has a tensile strength between 100 and 600 MPa, it has a low density of approximately 2.7 g/cm³, and a high strength to weight ratio of around 200 to 350 kN·m/kg (kilonewton meter per kilogram)[3]. Moreover, it has a fair welding ability and good corrosion resistance.

- **Steel:** steel has a high tensile strength ranging from 400 to 700 MPa depending on the type of alloy, however it has a high density ranging from 7.75 to 8.05 g/cm³, and a low strength to weight ratio of about 50 to 200 kN.m/kg. Steel also provides a good welding ability, and very good corrosion resistance.

- **Acrylic:** acrylic has a low tensile strength of about 55 to 80 MPa, but it also has a low density of around 1.17 to 1.2 g/cm³, providing a strength to weight ratio of 45 to 70 kNm/kg. This material too has a good welding ability and is corrosion resistant.

3.5.2 Selection of Magnets

In this project we have implemented magnetic adhesion technique for climbing over vertical boiler walls. There are various kinds of magnets to choose from; one that best suits your need. Wall climbing robots have certain weight and gravitational forces acting on robot while climbing vertical wall. Neodymium(N35) magnets are chosen for this operation, these magnets offer great adhesion and have high payload capacity. A round neodymium magnet with a diameter of 20mm and a thickness of 3mm has a pull force of approximately 3.6kg.

Figure 31: Round-shaped N35(neodymium) magnets

Once decided upon the material of magnets, the next step is to select the right shape to use for the robot. According to a study, shape of a magnet can highly affect the adhesion of these magnets[21]. Nevertheless, certain factors need to be considered to evaluate these in real-world scenarios. In one scenario, when ring magnets are used in the wheels for providing adhesion, additional wheels are not required for locomotion. Whereas the block magnets additional wheels are required which will add to the weight of the robot.

So, the wheels are designed using ring magnets or cylindrical shaped magnets. And extra coating material (for instance rubber) that surrounds the magnets and prevent them from direct contact with the surface. Figure 19 shows the magnetic wheel design for the robot.

3.5.3 Assembling and Manufacturing the Parts

Considering the robot was required to climb walls while moving against gravity so our main selection criteria was to have a low weight while having good strength, so aluminum was selected since it has the highest strength to weight ratio among these materials.

Robot fabrication is an important phase of this project. After careful modelling of robot design and running various simulations, the team worked together on manufacturing the robot, one part at a time. As mentioned in the above sections, material selection was done so that weight of the base can be optimized. These are the main steps of bringing the robot into the physical environment.

1. At the very first step we focused on the manufacturing of magnetic wheels; that provided robot locomotion as well as adhesion capability. Parts of wheel are the rim, shaft (connected to motor), magnets, framework. The rim of the wheel is casted from aluminum and the shaft is made of steel is merged with it.

Figure 33: Rim of the wheel; casted with Aluminum

Figure 32: Shafts for the wheel

2. Magnets are fixed over the rim with the help of a framework. This framework offers friction for the tires to move upward as well as keep the magnets in place. This frame also keeps the magnets from wear and tear by maintaining a little clearance (about 1mm) between the metal surface and magnets. This figure illustrates the wheel design for the robot.

Figure 34: Magnetic wheel

3. Robot's weight is supported by its base structure. Aluminum was used to are this structure, over which motors and other components are mounted. It is important to note that the major consideration at this stage has been for the robot's weight be kept minimum.
4. Robt's control system consists of the microcontroller, motor drivers, motors, camera module etc. This complete circuit is fabricated into a PCB. This acts as the computer system of the robot.

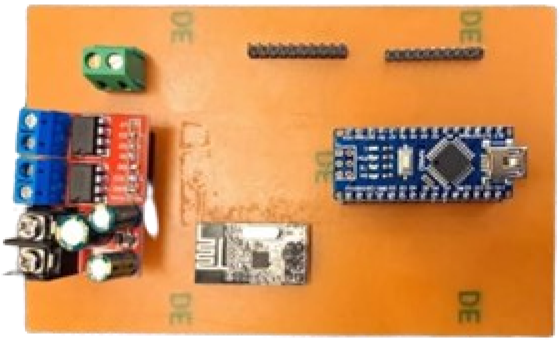


Figure 35: PCB of the motion control circuit

5. Robot's circuits and other electronic units ought to be protected from the water spillage, for which a water protective case is designed in Solid works and then 3D printed to keep the Control System safe. It

is then mounted over the base. Below, is the final robot after passing through all the phases of fabrication.

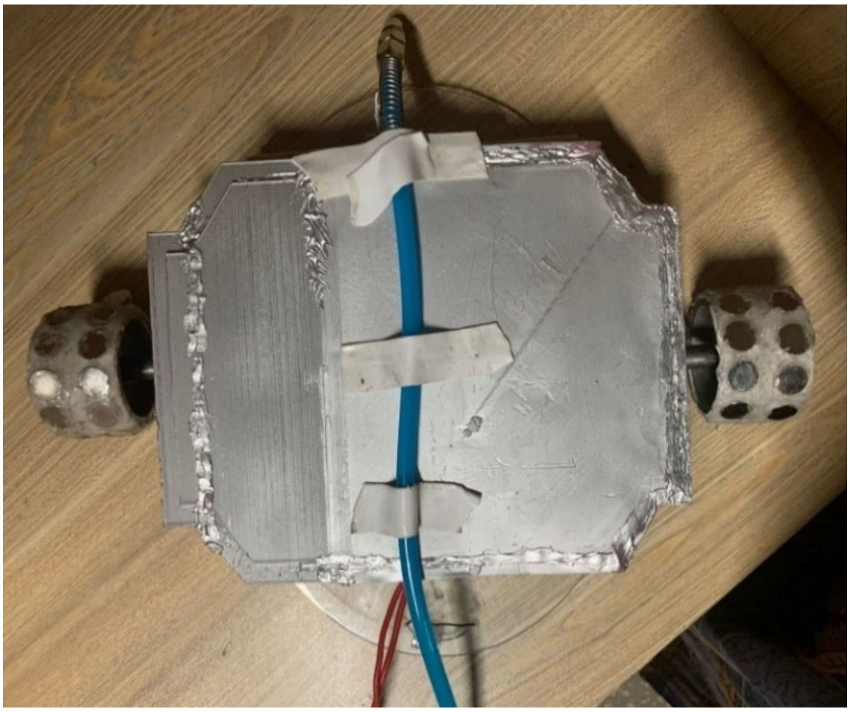


Figure 36: Final Robot Design

Chapter 4 - RESULTS

4.1 Analysis

In the development of the wall climbing robot for cleaning and inspection of boilers, various types of analysis have been conducted to assess and optimize critical components. Fluid analysis, magnetic analysis, and static analysis have been performed on the water jet, wheel magnets, and robot base, respectively. These analyses play a significant role in evaluating the performance, functionality, and structural integrity of these components, ensuring the overall effectiveness and reliability of the robot's operation.

Analysis plays a critical role in the development of the wall climbing robot for cleaning and inspection of boilers, as it enables a comprehensive understanding of the robot's performance, capabilities, and potential improvements. By conducting various analyses, we can assess the structural integrity, motion characteristics, and efficiency of the robot, ensuring its safe and effective operation in real-world scenarios.

One of the key reasons for conducting analysis is to identify and mitigate potential design flaws or weaknesses. Through structural analysis, we can evaluate the robot's ability to withstand the forces and stresses encountered during climbing and cleaning operations. This analysis helps us identify critical areas that may require reinforcement or modification to ensure the robot's longevity and reliability.

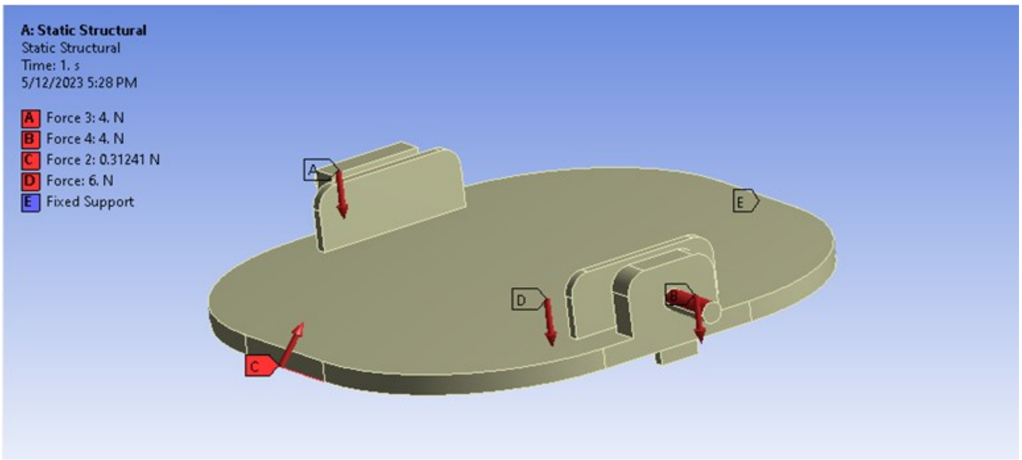
The static analysis focused on the robot's base, which is subjected to various mechanical loads and stresses. By simulating and analyzing the structural response, we assessed factors such as deformation, stress concentration, and load-bearing capacity. This analysis aids in identifying weak points and determining suitable reinforcement strategies to ensure the base's structural integrity and overall robustness. The magnetic analysis involved evaluating the magnetic properties and forces exerted by the magnets on the robot's wheels. By studying the magnetic field distribution, we assessed factors like magnetic attraction and repulsion, ensuring proper wheel adhesion to the boiler walls. This analysis aids in optimizing the magnetic strength and positioning to provide sufficient traction and stability during climbing.

4.1.1 Static Structural Analysis

We conducted static structural analysis on several parts of our CAD model using the finite element analysis method on ANSYS. The purpose of this analysis was to identify stress concentration areas experienced by the base of our robot. The results of this analysis helped us to choose the best material and modify the shape of our design to reduce stress and prevent deformation.

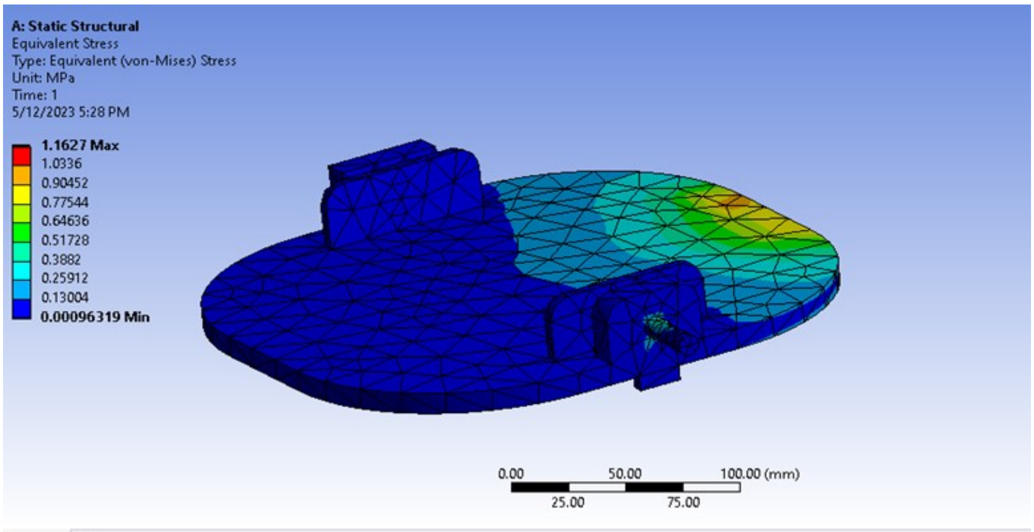
To perform this analysis, we meshed the base and performed calculations for each individual element. The software provided an overall result of the structure by combining these results.

Figure 37 below shows the forces acting on the base, including the weight at the center, forces experienced by the shafts, and the force of the water jet on the base. Figure 38 shows the equivalent von-Mises stress on the base, indicating that most of the base has a minimum stress value of 0.00096 MPa, while the shafts and front side of the base have higher stress. The maximum stress value is 1.03 MPa while maximum allowable stress for aluminum is 65.5 MPa and greater for different alloys. So, this provides a factor of safety of 63.5, providing conditions far from hazardous. Figure 39 shows the total deformation of the base, revealing a maximum deformation at the location where the jet is connected. A general value for maximum allowable strain for aluminum is 0.002 and with our model length of 228mm, the allowable deformation is 0.45mm while the maximum deformation for this model is only 0.03 mm providing a factor of safety of 15, which is not a cause for concern.



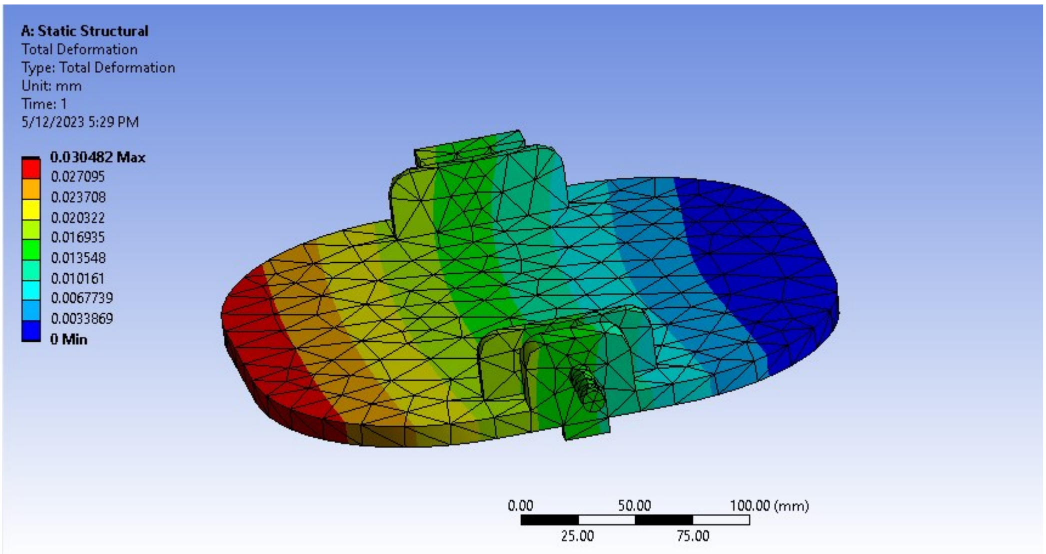
A: Static Structural
Static Structural
Time: 1. s
5/12/2023 5:28 PM

Figure 37: Forces acting on the base



A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
5/12/2023 5:28 PM

Figure 38: Equivalent stress



A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
5/12/2023 5:29 PM

Figure 39: Total Deformation

4.1.2 Magnetostatic Analysis

We conducted a magnetostatic analysis on our magnetic wheel design using EMS in SolidWorks. Neodymium magnet was chosen as the material for all the magnets, and we performed two analyses by changing the coercivity direction of the magnets. This analysis aided us in determining the position of the magnets to obtain the highest magnetic flux density.

Initially, the coercivity direction of the magnets of the two rows was oriented towards each other, as shown in Figure 40. We then performed calculations using the software to determine the magnetic flux intensity and magnetic flux density. Figure 41 shows the magnetic flux intensity, where the outer side of the wheel towards the center reaches a maximum value of $5.46 \times 10^5 Amp/m$. Figure 42 displays the magnetic flux density, which attains a maximum value of 79.7 Tesla on the outer rim towards the center.

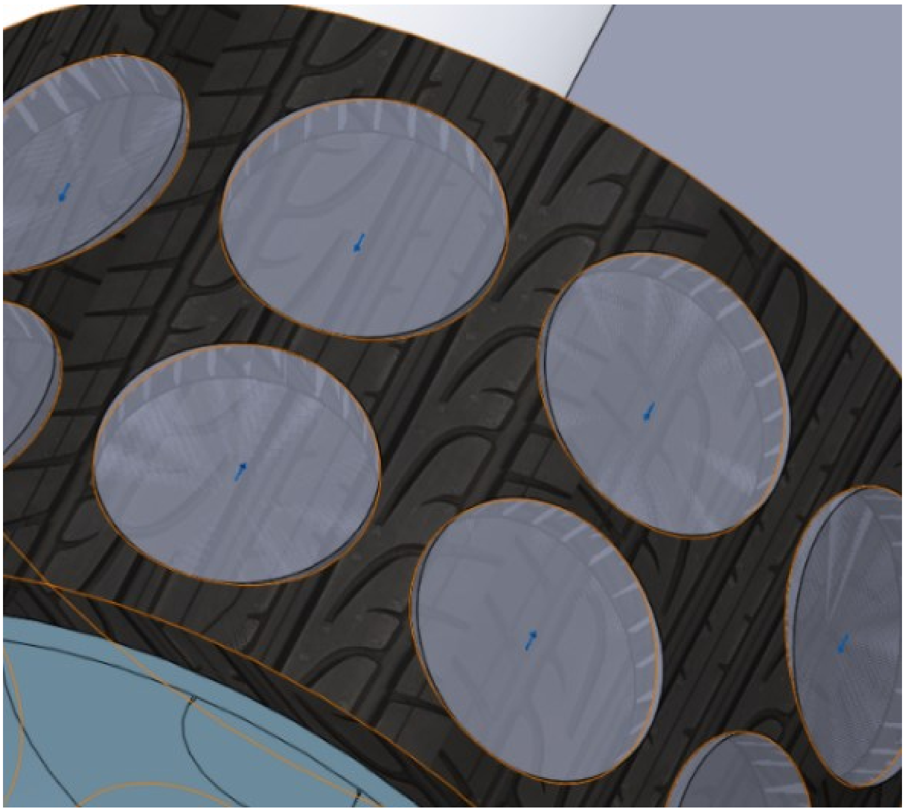


Figure 40: Coercivity Direction Towards Each other

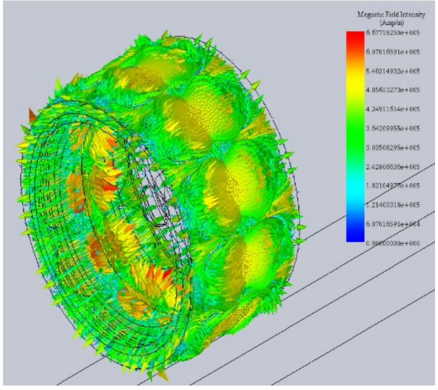


Figure 41: Magnetic Flux Intensity

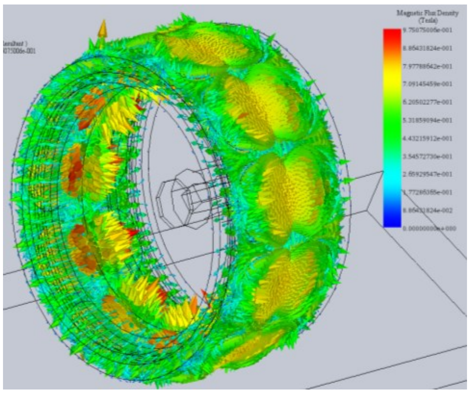


Figure 42: Magnetic Flux Density

Afterwards, we changed the coercivity direction of the magnets, so that both rows faced away from each other, as depicted in Figure 43. We then conducted magnetic analysis to determine the magnetic flux intensity and density. Figure 44 displays the magnetic flux intensity, which reaches a maximum value of $6.9 \times 10^5\ Amp/m$ towards the outer part of the wheel at the center providing a 26.4% increase in value. Figure 45 shows the magnetic flux density, which reaches a maximum value of 96.7 Tesla at the sides of the wheel, providing a percentage increase of 21.3%. Based on the results of these two analyses, we concluded that magnets with a coercivity direction away from each other produce greater magnetic flux intensity and magnetic flux density. Furthermore, analysis was done by adding a layer of magnets to determine the pattern of increase in magnetic force intensity and density by increasing the number of magnets. The results of magnetic analysis with 33 number of magnets is shown in Annex.

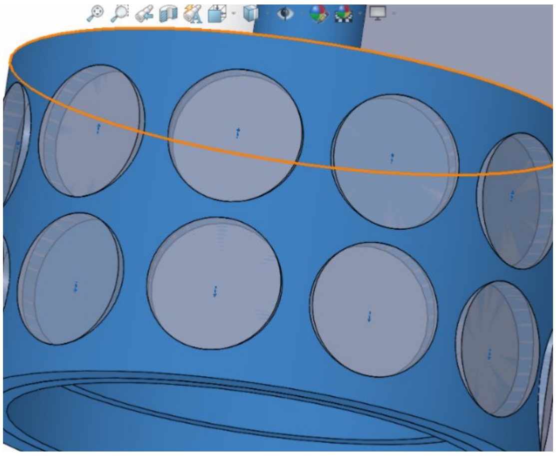


Figure 43: Coercivity Direction Facing Away from Each other

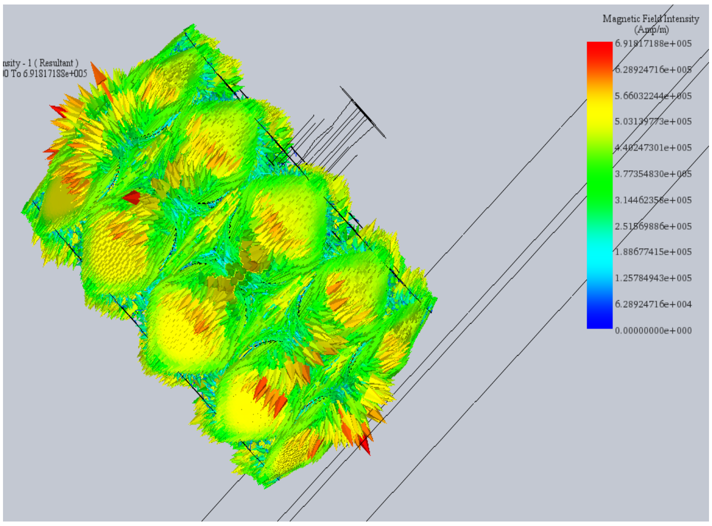


Figure 44: Magnetic Flux Intensity

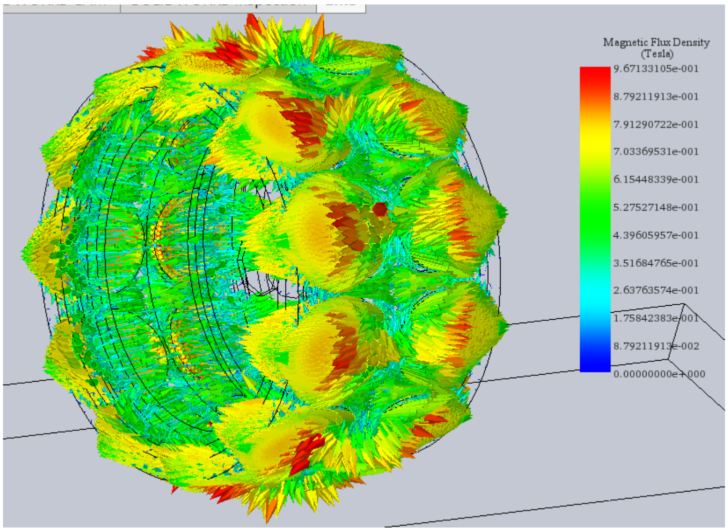


Figure 45: Magnetic Flux Density

Table 2: Properties of Magnets with Respect to the Orientation

Sr.	Number of Magnets	Coercivity Direction	Force Intensity 10^5 *A/m*	Force Density *Tesla*
1.	22	Facing Each other	5.46	79.7
2.	22	Acing Opposite	6.9	9.67
3	33	Acting Opposite	7.20	9.87

4.1.3 Fluid Analysis

Flow simulation analysis was done on SolidWorks to determine the velocity and speed of the desired nozzle. This analysis is used to determine the velocity of water flow at the start and end of the nozzle. In this model the maximum velocity at the output is $20.7\, m/s$ while the inlet velocity is 2.3m/s, hence providing 8 times increase in velocity, as shown in Figure 46. Moreover, pressure is determined at the start and end of the nozzle to ensure that it fulfills pressure requirements. The Figure 47 shows that for a pressure of 101616 Pa at inlet we obtain a pressure of 101297 Pa at outlet, which provides a 0.3% decrease in pressure value for this nozzle design.

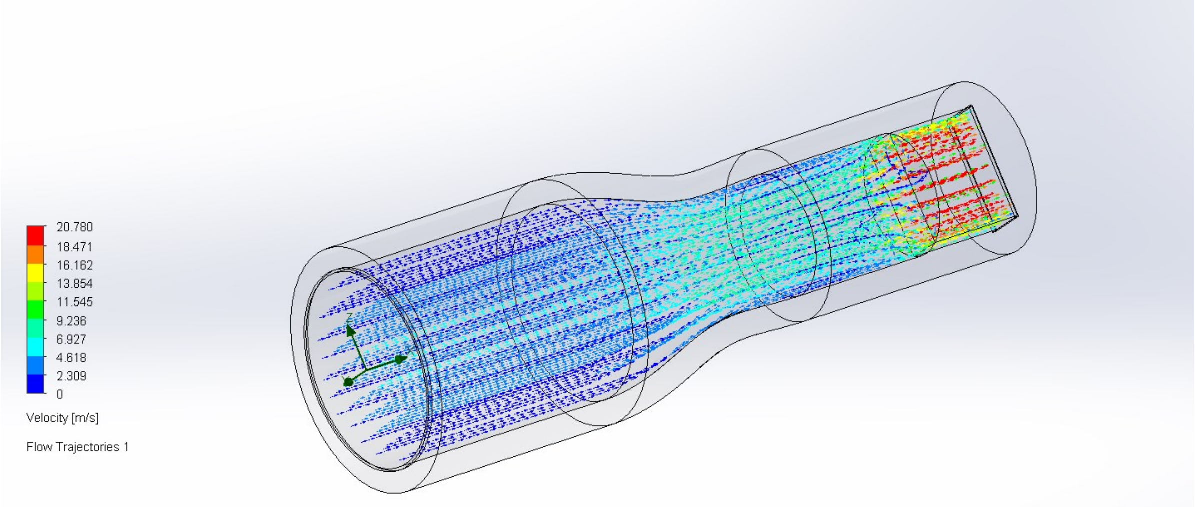


Figure 46: Velocity of water jet through nozzle

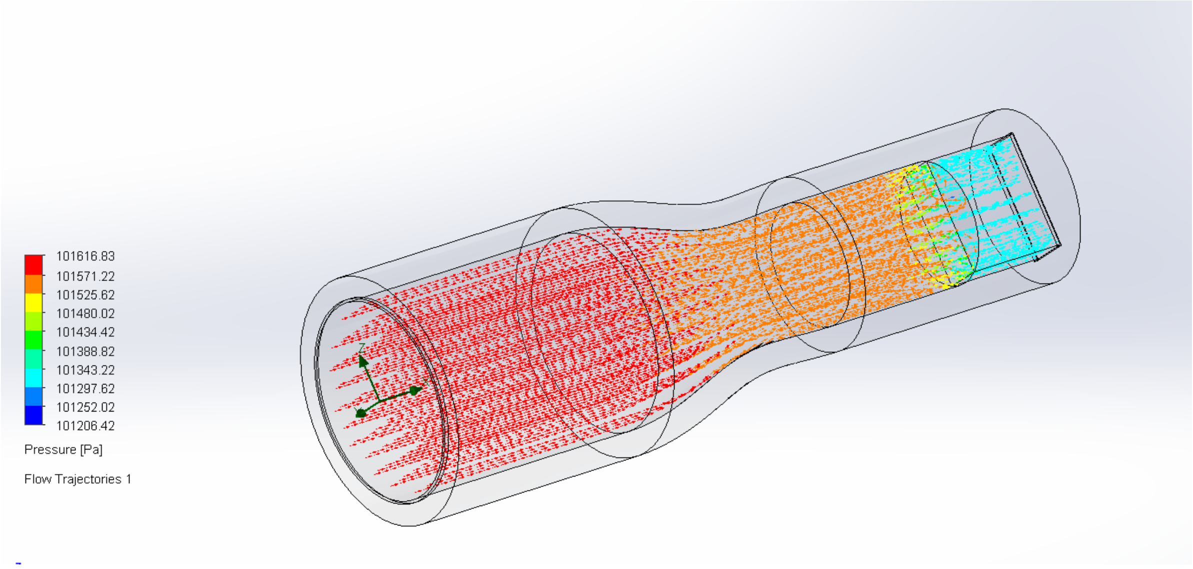


Figure 47: Pressure of water jet through nozzle

CHAPTER 5 - CONCLUSION AND FUTURE WORK

With rapid growth in the industrial and agricultural sectors, the use of boilers will increase with each passing day. Regular maintenance and cleaning are required for the efficient operation of these boilers, and they must be completed rapidly to keep up with the world's rapid pace of change. This is essential to several industries, including the textile, fertilizer, and food sectors, without which businesses, farmers, and consumers would all suffer. Therefore, in order to provide a quicker, safer, and more effective inspection and cleaning mechanism for these boilers, the employment of wall-climbing robots will grow.

5.1 Achieved Milestones

Only through great determination can one achieve great results. This project addresses this issue by creating a wall-climbing robot that can scale steel walls and is outfitted with a camera for inspection and a water jet system for cleaning. Following are the outcomes of the project:

1. To design a reliable robot, careful examination of the locomotion and adhesion techniques was done, which determines the payload capacity, moving velocity, and steering ability of the WCR. A thorough examination was done for four locomotion techniques i.e., crawlers, wheeled, legged and hybrid, and wheels were selected as the locomotion technique that provide a medium pay load capacity and are faster compared to other methods.
2. For the adhesion mechanism, the methods reviewed were negative pressure adsorption, magnetic adhesion, bionic and electrostatic adhesion. Taking into consideration the strength and reliability of adhesion, permanent magnetic adhesion was selected which provides a high payload capacity and most reliable adhesion for ferromagnetic surfaces as compared with other methods.
3. For this project both the locomotion and adhesion techniques were integrated together to make magnetic wheels. Which comprised of magnets attached at

the outer rim of the wheel surrounded by a rubber coating to provide friction and prevent magnets from wear and tear.

4. Various non-destructive testing techniques were researched, in order to conduct inspections of boiler walls. Camera was selected to provide real-time visual data to the supervisor on a PC through wireless communication. The video display can be utilized to identify ruptured pipes, tube enlargements, and pinhole leaks. If not detected in time, these issues can cause significant damage to the boiler during operation.
5. Additionally, a water jet cleaning system was integrated onto the robot to clean the tubes from sludge deposits and other residues, which are common in boilers. Moreover, the system is equipped with a solenoid valve to control the water jet, ensuring it is only activated where necessary and preventing any water wastage.

This project aims to offer a locally available solution that enhances the efficiency of the cleaning process while providing a safe working environment for the personnel involved.

5.2 Operating Instructions

This project uses permanent magnets for adhesion of robot to maneuver over boiler walls. Following are the robot specifications or features that will assist in understanding it's operation:

1. Transition from ground to wall is challenging for the robot to perform, considering this it must be deployed manually to start its cleaning and inspection operation.
2. There are two robot extensions hanging to it, one is the supply wire. While the other one is the water pipe that carries water for the water jet. These are ought to be plugged for robot to start operations.
3. A constant water and power supply must be available.
4. Mount the water-proof case before operation of robot so that any water spillage could be avoided.
5. The live transmission of esp32 cam is obtained over Wi-Fi, the network that is chosen for transmission must be stable.

6. Robot can climb only walls that are ferromagnetic, non-ferromagnetic or other surfaces that are rough should be avoided because it may cause the wheels to wear.

5.3 Marketing Strategy

Among fertilizer manufacturing companies, Fauji fertilizer had a market share of 51% in 2020. They are looking for a locally available solution for cleaning their boilers. Vertical wall work is inevitable, as discussed previously, this industry is vast. Attention should be paid to a good business plan to launch this robot as a product. The application is not limited to boiler cleaning and inspection but various other types of chores that require high risk and are not feasible to executed by humans. This project already has a target audience that is monitoring the progress of the project. The following steps are taken to develop a successful product development strategy.

The project is at the initial stages of its development, constant work and development should be done under supervision to reap great results.

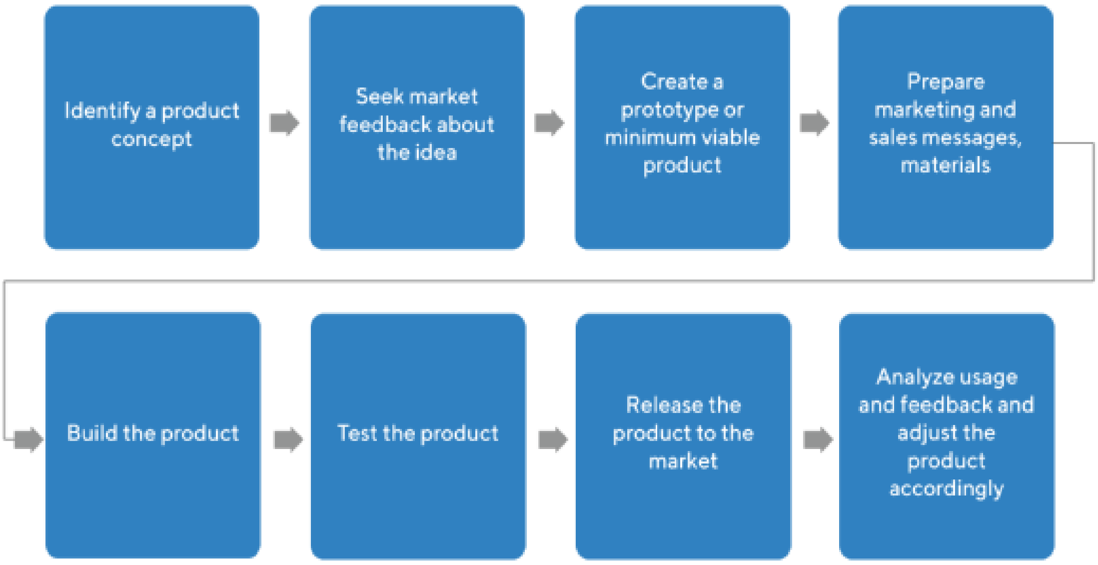


Figure 48: Marketing Strategy of the Project

5.4 Future Direction

This study enabled us to provide a novel solution to wall-climbing problem. The wall-climbing robot can climb the walls, clean them and get a visual for the condition walls are in. However, this study should be expanded for more accurate and real applications. Following are different fields of interest that should be considered for research in the coming years:

- Inspection Methods: Current inspection mechanism collects footage of walls; this is displayed at a monitor connected to it. Further study should be conducted to use artificial intelligence and other image processing techniques to process this data and derive results. The video being transmitted to the computer can be collected and stored. By incorporating artificial intelligence into the camera's visual data analysis, defects can be detected without human interaction during inspections.

- Non-Destructive Testing: This WCR could be equipped with ultrasonic sensors to accurately measure tube thickness, enabling the detection of erosion or corrosion.

- Cleaning Methods: Furthermore, the robot can be scaled up allowing for the addition of multiple water jet nozzles, enabling the simultaneous cleaning of multiple tubes, and significantly expediting the cleaning process.

By producing and manufacturing these robots, Pakistan can position itself as a global provider of a highly sought-after solution, leading to a substantial boost in the country’s economy.

REFERENCES

[1] J. Jin-Gang, Z. Yong-De, and Z. Shu, “Implementation of glass-curtain-wall cleaning robot driven by double flexible rope,” Industrial Robot, vol. 41, no. 5, pp. 429–438, Aug. 2014, doi: 10.1108/IR-01-2014-0303.

[2] G. Andrikopoulos and G. Nikolakopoulos, “Design, Development and Experimental Evaluation of a Vortex Actuation System,” 2018 14th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications, MESA 2018, Aug. 2018, doi: 10.1109/MESA.2018.8449151.

[3] J. Xiao, B. Li, K. Ushiroda, and Q. Song, “Rise-Rover: A wall-climbing robot with high reliability and load-carrying capacity,” 2015 IEEE International Conference on Robotics and Biomimetics, IEEE-ROBIO 2015, pp. 2072–2077, 2015, doi: 10.1109/ROBIO.2015.7419079.

[4] B. Li, K. Ushiroda, L. Yang, Q. Song, and J. Xiao, “Wall-climbing robot for non-destructive evaluation using impact-echo and metric learning SVM,” Int J Intell Robot Appl, vol. 1, no. 3, pp. 255–270, Sep. 2017, doi: 10.1007/S41315-017-0028-4/FIGURES/19.

[5] R. Siegwart, “Compact magnetic wheeled robot with high mobility for inspecting complex shaped pipe structures,” 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, Jan. 2007, Accessed: Aug. 31, 2022. [Online]. Available: https://www.academia.edu/15153113/Compact_magnetic_wheeled_robot_with_high_mobility_for_inspecting_complex_shaped_pipe_structures

[6] Y. Zhang, T. Dodd, K. Atallah, and I. Lyne, “Design and optimization of magnetic wheel for wall and ceiling climbing robot,” undefined, pp. 1393–1398, 2010, doi: 10.1109/ICMA.2010.5589061.

[7] J. Guo, L. Justham, M. Jackson, and R. Parkin, “A concept selection method for designing climbing robots,” Key Eng Mater, vol. 649, pp. 22–29, 2015, doi: 10.4028/WWW.SCIENTIFIC.NET/KEM.649.22.

[8] I. Mo et al., “Development of Wall Climbing Robot System by Using Impeller Type Adhesion Mechanism,” Journal of Intelligent & Robotic Systems 2013 72:1, vol. 72, no. 1, pp. 57–72, Feb. 2013, doi: 10.1007/S10846-013-9820-Z.

[9] Y. Fang, S. Wang, D. Cui, Q. Bi, R. Jiang, and C. Yan, “Design and optimization of wall-climbing robot impeller by genetic algorithm based on computational fluid dynamics and kriging model,” 123AD, doi: 10.1038/s41598-022-13784-z.

[10] Y. Fang, S. Wang, Q. Bi, D. Cui, and C. Yan, “Design and Technical Development of Wall-Climbing Robots: A Review,” J Bionic Eng, vol. 19, no. 4, pp. 877–901, Jul. 2022, doi: 10.1007/S42235-022-00189-X/TABLES/3.

[11] H. Eto and H. H. Asada, “Development of a Wheeled Wall-Climbing Robot with a Shape-Adaptive Magnetic Adhesion Mechanism,” Proc IEEE Int Conf Robot Autom, pp. 9329–9335, May 2020, doi: 10.1109/ICRA40945.2020.9196919.

[12] S. K. Mahmood, S. H. Bakhy, and M. A. Tawfik, “Magnetic–type Climbing Wheeled Mobile Robot for Engineering Education,” IOP Conf Ser Mater Sci Eng, vol. 928, no. 2, p. 022145, Nov. 2020, doi: 10.1088/1757-899X/928/2/022145.

[13] H. Zhu, S. Gu, L. He, Y. Guan, and H. Zhang, “Transition Analysis and Its Application to Global Path Determination for a Biped Climbing Robot,” Applied Sciences 2018, Vol. 8, Page 122, vol. 8, no. 1, p. 122, Jan. 2018, doi: 10.3390/APP8010122.

[14] “(PDF) DESIGN & DEVELOP THE PROTOTYPE OF WALL CLIMBING ROBOT.” https://www.researchgate.net/publication/285735772_DESIGN_DEVELOP_THE_PROTOTYPE_OF_WALL_CLIMBING_ROBOT (accessed Aug. 31, 2022).

[15] Y.-B. Chang, “Development of a wall climbing inspection robot with high mobility on complex shaped walls.,” undefined, 2015, doi: 10.26021/2555.

[16] R. Liu and R. Liang, “Design of a Docking Wall-Climbing Robot:,” https://doi.org/10.5772/53781, vol. 10, Jan. 2013, doi: 10.5772/53781.

[17] J. Zhu, D. Sun, and S. K. Tso, “Development of a Tracked Climbing Robot,” Journal of Intelligent and Robotic Systems 2002 35:4, vol. 35, no. 4, pp. 427–443, 2002, doi: 10.1023/A:1022383216233.

[18] Y. W. K. W. A. Nishi, “Design of a robot capable of moving on a vertical wall,” Advanced Robotics, vol. 1, no. 1, pp. 33–45, 1986.

[19] A. Nishi, Y. Wakasugi, and K. Watanabe, “Design of a robot capable of moving on a vertical wall,” http://dx.doi.org/10.1163/156855386X00300, vol. 1, no. 1, pp. 35–45, 2012, doi: 10.1163/156855386X00300.

[20] J. Jose, D. Dinakaran, M. M. Ramya, and D. G. Harris Samuel, “A survey on magnetic wall-climbing robots for inspection,” International Journal of Mechanical and Production Engineering Research and Development, vol. 8, no. 6, pp. 59–68, 2018, doi: 10.24247/IJMPERDDEC20186.

[21] “A Comparative Study of Adhesion Mechanism for Wall Climbing Robots: Ring Magnet vs. Block Magnets - IOPscience.” https://iopscience.iop.org/article/10.1088/1757-899X/1145/1/012063/meta (accessed Aug. 31, 2022).

[22] L. P. Kalra, J. Gu and M. Meng, "A Wall Climbing Robot for Oil Tank Inspection," 2006 IEEE International Conference on Robotics and Biomimetics, 2006, pp. 1523-1528, doi: 10.1109/ROBIO.2006.340155.

[23] J. Shao et al., "A wall-climbing robot with gecko features," 2012 IEEE International Conference on Mechatronics and Automation, 2012, pp. 942-947, doi: 10.1109/ICMA.2012.6283270.

[24] Schmidt, Daniel & Hillenbrand, Carsten & Berns, Karsten. (2011). Omnidirectional locomotion and traction control of the wheel-driven, wall-climbing robot, CROMSCI. Robotica. 29. 991-1003. 10.1017/S0263574711000294.

[25] Park, Sangdeok & Jeong, Hee & Lim, Zhong. (2003). Design of a Mobile Robot System for Automatic Integrity Evaluation of Large Size Reservoirs and Pipelines in Industrial Fields. 3. 2618 - 2623 vol.3. 10.1109/IROS.2003.1249265.

[26] Luk, B.L. & White, T.S. & Cooke, D.S. & Hewer, N.D. & Hazel, G.. (2001). Climbing service robot for duct inspection and maintenance applications in a nuclear reactor.

[27] Hongjun Chen, Weihua Sheng, Ning Xi and Jindong Tan, "Motion Control of a Micro Biped Robot for Nondestructive Structure Inspection," Proceedings of the 2005 IEEE

International Conference on Robotics and Automation, 2005, pp. 478-483, doi: 10.1109/ROBOT.2005.1570164.

[28] A. Ariga, T. Kobayashi, T. Yamaguchi and S. Hashimoto, "Wall climbing robot in narrow space with pantograph-type structure," 2010 IEEE International Conference on Robotics and Biomimetics, 2010, pp. 1507-1512, doi: 10.1109/ROBIO.2010.5723553.

[29] Zhang, Houxiang & Liu, Rong & Zong, Guanghua & Zhang, Jianwei. (2006). A Novel Autonomous Climbing Robot for Cleaning an Elliptic Half-Shell. 10.5772/4711.

[30] H. Albitar, A. Ananiev and I. Kalaykov, "New concept of in-water surface cleaning robot," 2013 IEEE International Conference on Mechatronics and Automation, 2013, pp. 1582-1587, doi: 10.1109/ICMA.2013.6618150.

[31] Houxiang Zhang, Jianwei Zhang, Rong Liu and Guanghua Zong, "A novel approach to pneumatic position servo control of a glass wall cleaning robot," 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE Cat. No.04CH37566), 2004, pp. 467-472 vol.1, doi: 10.1109/IROS.2004.1389396.

[32] Zhengyao Yi, Yongju Gong, Zuwen Wang and Xingru Wang, "Development of a wall climbing robot for ship rust removal," 2009 International Conference on Mechatronics and Automation, 2009, pp. 4610-4615, doi: 10.1109/ICMA.2009.5244801.

[33] Xiao, Jizhong & Sadegh, Ali. (2007). City-Climber: A New Generation Wall-Climbing Robots. 10.5772/5090.

[34] Wei Guo, Ming Zhong, Man-tian Li and Yang Li, "Design of a six-legged wall-climbing robot," 2008 IEEE Workshop on Advanced robotics and Its Social Impacts, 2008, pp. 1-4, doi: 10.1109/ARSO.2008.4653597.

[35] Kim, H., Kim, D., Yang, H. et al. Development of a wall-climbing robot using a tracked wheel mechanism. J Mech Sci Technol **22**, 1490–1498 (2008)

[36] Xu, Zeliang & Ma, Peisun. (2002). A wall-climbing robot for labeling scale of oil tank's volume. Robotica. 20. 209-212. 10.1017/S0263574701003964.

[37] H. Schempf, B. Chemel and N. Everett, "Neptune: above-ground storage tank inspection robot system," in IEEE Robotics & Automation Magazine, vol. 2, no. 2, pp. 9-15, June 1995, doi: 10.1109/100.392414.

[38] R. T. Pack, J. L. Christopher and K. Kawamura, "A Rubbertuator-based structure-climbing inspection robot," Proceedings of International Conference on Robotics and Automation, 1997, pp. 1869-1874 vol.3, doi: 10.1109/ROBOT.1997.619060.

[39] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, V. Mattoli and M. R. Cutkosky, "Whole body adhesion: hierarchical, directional and distributed control of adhesive forces for a climbing robot," Proceedings 2007 IEEE International Conference on Robotics and Automation, 2007, pp. 1268-1273, doi: 10.1109/ROBOT.2007.363159.

[40] O. Unver, A. Uneri, A. Aydemir and M. Sitti, "Geckobot: a gecko inspired climbing robot using elastomer adhesives," Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006., 2006, pp. 2329-2335, doi: 10.1109/ROBOT.2006.1642050.

[41] A. San-Millan, “Design of a teleoperated wall climbing robot for oil tank inspection,” in 2015 23rd Mediterranean Conference on Control and Automation, MED 2015 - Conference Proceedings, Institute of Electrical and Electronics Engineers Inc., Jul. 2015, pp. 255–261. doi: 10.1109/MED.2015.7158759.

[42] “Coefficient of Friction Equation and Table Chart.” https://www.engineersedge.com/coeffients_of_friction.htm (accessed May 22, 2023).

[43] “Mechanical Properties of Various Alloys - Knowledgebase - FAQ - Help Center - The Wagner Companies.” https://kb.wagnercompanies.com/knowledge-base/mechanical-properties-of-various-alloys/ (accessed May 22, 2023).

[44]“A Comparative Study of Adhesion Mechanism for Wall Climbing Robots: Ring Magnet vs. Block Magnets - IOPscience.” https://iopscience.iop.org/article/10.1088/1757-899X/1145/1/012063/meta (accessed Aug. 31, 2022).

ANNEX

ARDUINO CODE

```
// motor left
#define ENCAL 2
#define PWML_F 5
#define PWML_R 6
// motor right
#define ENCAR 3
#define PWMR_F 10
#define PWMR_R 9
// globals
long prevT = 0;
int posPrev1 = 0;
int posPrev2 = 0;
volatile int pos_i1 = 0;
volatile int pos_i2 = 0;
volatile float velocity_i1 = 0;
volatile float velocity_i2 = 0;
volatile long prevT_i1 = 0;
volatile long prevT_i2 = 0;
unsigned long Time;
```

```
float v1Filt = 0; //motor 1..LEFT

float v1Prev = 0;

float v2Filt = 0; //motor 2...RIGHT

float v2Prev = 0;

float eintegral1 = 0;

float eintegral2 = 0;

void setup() {

Serial.begin(115200);

pinMode(ENCAL,INPUT);

pinMode(PWML_F,OUTPUT);

pinMode(PWML_R,OUTPUT);

pinMode(ENCAR,INPUT);

pinMode(PWMR_F,OUTPUT);

pinMode(PWMR_R,OUTPUT);

attachInterrupt(digitalPinToInterrupt(ENCAL),readEncoder1,RISING);

attachInterrupt(digitalPinToInterrupt(ENCAR),readEncoder2,RISING);

}

void loop() {

while(pos_i1 <= 600)

{ moveforward();   } //moving upwards

Stop();

delay(100);

Time = millis();

while(millis() <= Time+900) //taking 90 deg right turn
```

```
{ TurnRight();}

Stop();

delay(200);

pos_i1=0;

while(pos_i1 <= 100) //moving straight

{ moveforward();}

Stop();

delay(200);

Time = millis();

while(millis() <= Time+900) //taking 90 degree left turn

{ TurnLeft();}

Stop();

delay(200);

pos_i1=0;

while(pos_i1 <= 600)

{ movereverse();   } //moving downwards in reverse

Stop();

delay(100);

}

void readEncoder1(){

pos_i1 = pos_i1 + 1;

long currT1 = micros();

float deltaT1 = ((float) (currT1 - prevT_i1))/1.0e6;

velocity_i1 = 1/deltaT1;
```

```
prevT_i1 = currT1;

}

void readEncoder2(){

pos_i2 = pos_i2 + 1;

long currT2 = micros();

float deltaT2 = ((float) (currT2 - prevT_i2))/1.0e6;

velocity_i2 = 1/deltaT2;

prevT_i2 = currT2;

}

void TurnRight()

{

analogWrite(PWML_F,130);

analogWrite(PWML_R,0);

analogWrite(PWMR_F,0);

analogWrite(PWMR_R,130);

}

void TurnLeft()

{

analogWrite(PWML_F,0);

analogWrite(PWML_R,130);

analogWrite(PWMR_F,130);

analogWrite(PWMR_R,0);

}

void Stop()
```

```
{
analogWrite(PWML_F,0);
analogWrite(PWML_R,0);
analogWrite(PWMR_F,0);
analogWrite(PWMR_R,0);
}
void moveforward()
{
float velocity1 = 0;
float velocity2 = 0;
noInterrupts(); // disable interrupts temporarily while reading
velocity1 = velocity_i1;
velocity2 = velocity_i2;
interrupts(); // turn interrupts back on
long currT = micros();
float deltaT = ((float) (currT-prevT))/1.0e6;
prevT = currT;
//calculating rpm
float v1 = velocity1*60/700;  //RPM=(PR1)∗60/PPR∗GR
float v2 = velocity2*60/700;  //RPM=(PR1)∗60/PPR∗GR
// Low-pass filter (25 Hz cutoff)
v2Filt = 0.854*v2Filt + 0.0728*v2 + 0.0728*v2Prev;
v2Prev = v2;
v1Filt = 0.854*v1Filt + 0.0728*v1 + 0.0728*v1Prev;
```

```
v1Prev = v1;

// Set a target

float vt = 50;

// Compute the control signal u

float kp = 10;

float ki = 0.75;

float e1 = vt-v1;

float e2 = vt-v2;

eintegral1 = eintegral1 + e1*deltaT;

eintegral2 = eintegral2 + e2*deltaT;

float u1 = kp*e1 + ki*eintegral1;

float u2 = kp*e2 + ki*eintegral2;

// moving forward

int dir1 = 1;

int dir2 = 1;

int pwr1 = 210 + u1;

if(pwr1 > 255)

{pwr1 = 255;}

int pwr2 = 205 + u2;

if(pwr2 > 255)

{pwr2 = 255;}

setMotor(dir1,dir2,pwr1,pwr2,PWML_F,PWML_R,PWMR_F,PWMR_R);

delay(1);

}
```

```
void movereverse()
{
float velocity1 = 0;
float velocity2 = 0;
noInterrupts(); // disable interrupts temporarily while reading
velocity1 = velocity_i1;
velocity2 = velocity_i2;
interrupts(); // turn interrupts back on
long currT = micros();
float deltaT = ((float) (currT-prevT))/1.0e6;
prevT = currT;
//calculating rpm
float v1 = velocity1*60/700;  //RPM=(PR1)∗60/PPR∗GR
float v2 = velocity2*60/700;  //RPM=(PR1)∗60/PPR∗GR
// Low-pass filter (25 Hz cutoff)
v2Filt = 0.854*v2Filt + 0.0728*v2 + 0.0728*v2Prev;
v2Prev = v2;
v1Filt = 0.854*v1Filt + 0.0728*v1 + 0.0728*v1Prev;
v1Prev = v1;
// Set a target
float vt = 50;
// Compute the control signal u
float kp = 10;
float ki = 0.75;
```

```
float e1 = vt-v1;

float e2 = vt-v2;

eintegral1 = eintegral1 + e1*deltaT;

eintegral2 = eintegral2 + e2*deltaT;

float u1 = kp*e1 + ki*eintegral1;

float u2 = kp*e2 + ki*eintegral2;

// moving forward

int dir1 = -1;

int dir2 = -1;

int pwr1 = 210 + u1;

if(pwr1 > 255)

{pwr1 = 255;}

int pwr2 = 205 + u2;

if(pwr2 > 255)

{pwr2 = 255;}

setMotor(dir1,dir2,pwr1,pwr2,PWML_F,PWML_R,PWMR_F,PWMR_R);

delay(1);

}

void setMotor(int dir1,int dir2, int pwmVal1,int pwmVal2, int pwm1_f, int pwm1_r, int
pwm2_f, int pwm2_r){

if(dir1 == 1){

analogWrite(pwm1_f,pwmVal1);

analogWrite(pwm1_r,0);

}
```

```
else if(dir1 == -1){
analogWrite(pwm1_f,0);
analogWrite(pwm1_r,pwmVal1);
}
if(dir2 == 1){
analogWrite(pwm2_f,pwmVal2);
analogWrite(pwm2_r,0);
}
else if(dir2 == -1){
analogWrite(pwm2_f,0);
analogWrite(pwm2_r,pwmVal2);
}
}
```

MATLAB CODE

1. Kinematic Model

```
%% kinematic model of wall climbing robot

clear all; clc; close all;

%% Simulation parameters

dt = 0.1; % step size

ts = 100; % simulation time

t = 0:dt:ts; % time span

%% robot physical parameters

a = 0.2; % radius of wheel

d = 0.5; % distance between wheel frames

%% Initial conditions

x0 = 0.5;

y0 = 0;

psi0 = pi/2;

eta0 = [x0;y0;psi0];

eta(:,1) = eta0;

%% loop starts here

for i = 1: length(t)

psi = eta(3,i); %current orientation in rad

%% jacobain matrix

J_psi = [cos(psi), -sin(psi),0;

sin(psi), cos(psi),0;

0,0,1];

%% inputs
```

```
omega_1 = 0.5; % left wheel angular velocity
omega_2 = 0.5; % right wheel angular velocity
omega = [omega_1; omega_2];
%% wheel configuration matrix
W = [a/2,a/2;
0,0;
-a/(2*d), a/(2*d)];
% velocity input commands
zeta(:,i) = W*omega;
% time derivative of generlized coordinates
eta_dot(:,i) = J_psi * zeta(:,i);
% position propagation by euler method
eta(:,i+1) = eta(:,i) + dt*eta_dot(:,i);
end
% animation of bot
l = 0.3;
w = 0.2*d;
% co ordinates
mr_co = [-l, l, l, -1, -l;
-w, -w, w, w, -w;];
figure
for i = 1:5:length(t) % animation starts here
psi = eta(3,i);
R_psi = [cos(psi), -sin(psi);
sin(psi), cos(psi);]; % rotation matrix
v_pos = R_psi*mr_co;
```

```
fill(v_pos(1,:)+eta(1,i),v_pos(2,:)+eta(2,i),'g')

hold on, grid on; axis([-1 6 -1 6]), axis square

plot(eta(1,1:i), eta(2,1:i), 'b-');

legend('MR','Path')

set(gca,'fontsize',20)

xlabel('x,[m]'); ylabel('y,[m]');

pause(0.01);

hold off

end

%% plotting functions

figure

plot(t, eta(1,1:i), 'r-');

set(gca,'fontsize', 20)

xlabel('t,[s]');

ylabel('x,[m]');

figure

plot(t, eta(2,1:i), 'b-');

set(gca,'fontsize', 20)

xlabel('t,[s]');

ylabel('y,[m]');

figure

plot(t, eta(3,1:i), 'g-');

set(gca,'fontsize', 20)

xlabel('t,[s]');

ylabel('\psi,[rad]');
```

2. Dynamic Model of the Wall-climbing Robot

```
clear all; clc; close all;
%% Simulation parameters
dt = 0.1; % step size
ts = 10; % simulation time
t = 0:dt:ts; % time span
%% Initial conditions
eta0 = [0; 0; pi/4]; % initial position and orientation of the robot
zeta0 = [0; 2; 0]; % initial vector of input commands
eta(:, 1) = eta0;
zeta(:, 1) = zeta0;
%% Robot parameters
m = 2; % mass of robot
Iz = 0.1; % inertia of robot
l = 0.01; % length of robot (from mass center to the wall contact point)
g = 9.81; % acceleration due to gravity
xbc = 0; ybc = 0; % coordinates of mass center
%% State propagation
for i = 1:length(t)
u = zeta(1, i);
v = zeta(2, i);
r = zeta(3, i);
%% Inertia matrix
D = [m, 0, -ybc*m;
```

```
0, m, xbc*m;

-ybc*m, xbc*m, Iz+m*(xbc^2+ybc^2)];

%% Other vector

n_v = [-m*r*(v+xbc*r);

m*r*(u-ybc*r)-m*g;

m*r*(xbc*u+ybc*v)];

%% Input vector

tau(:, i) = [1; 0.5; 0];

%% Jacobian matrix

psi = eta(3, i);

J_eta = [cos(psi), -sin(psi), 0;

sin(psi), cos(psi), 0;

0, 0, 1];

%% Gravity compensation

F_gravity = [0; m*g; 0]; % gravity force in the world frame

F_gravity_local = J_eta' * F_gravity; % gravity force in the robot's local frame

%% Input vector with gravity compensation

tau(:, i) = tau(:, i) + F_gravity_local;

%% Dynamics calculation

zeta_dot(:, i) = inv(D) * (tau(:, i) - n_v);

zeta(:, i+1) = zeta(:, i) + dt * zeta_dot(:, i); % velocity update

eta(:, i+1) = eta(:, i) + dt * (J_eta * (zeta(:, i) + dt * zeta_dot(:, 1))); % state update

end

% animation of bot
```

```
l = 0.3;
w = 0.2;
% co ordinates
mr_co = [-l, l, l, -1, -l;
-w, -w, w, w, -w;];
figure
for i = 1:length(t) % animation starts here
psi = eta(3,i);
R_psi = [cos(psi), -sin(psi);
sin(psi), cos(psi);]; % rotation matrix
v_pos = R_psi*mr_co;
fill(v_pos(1,:)+eta(1,i),v_pos(2,:)+eta(2,i),'g')
hold on, grid on
l_lim = min(max(eta(1:2,:)));
u_lim = max(max(eta(1:2,:)));
axis([-5+l_lim 5+u_lim -5+l_lim 5+u_lim]), axis square
plot(eta(1,1:i), eta(2,1:i), 'b-');
legend('MR','Path')
set(gca,'fontsize',20)
xlabel('x,[m]'); ylabel('y,[m]');
pause(0.1);
hold off
end
%% Plotting functions
```

```
figure;
plot(t, eta(1, 1:i), 'r-', t, eta(2, 1:i), 'b-', t, eta(3, 1:i), 'k--', 'LineWidth', 2);
legend('x [m]', 'y [m]', '\psi [rad]');
set(gca, 'fontsize', 20);
grid on;
xlabel('t [s]');
ylabel('\eta [units]');
figure;
plot(t, zeta(1, 1:i), 'r-', t, zeta(2, 1:i), 'b-', t, zeta(3, 1:i), 'k--', 'LineWidth', 2);
legend('u [m/s]', 'v [m/s]', 'r [rad/s]');
set(gca, 'fontsize', 20);
grid on;
xlabel('t [s]');
ylabel('\zeta [units]');
```

APPENDICES

1. Magnetic Analysis with Three layers of Magnets

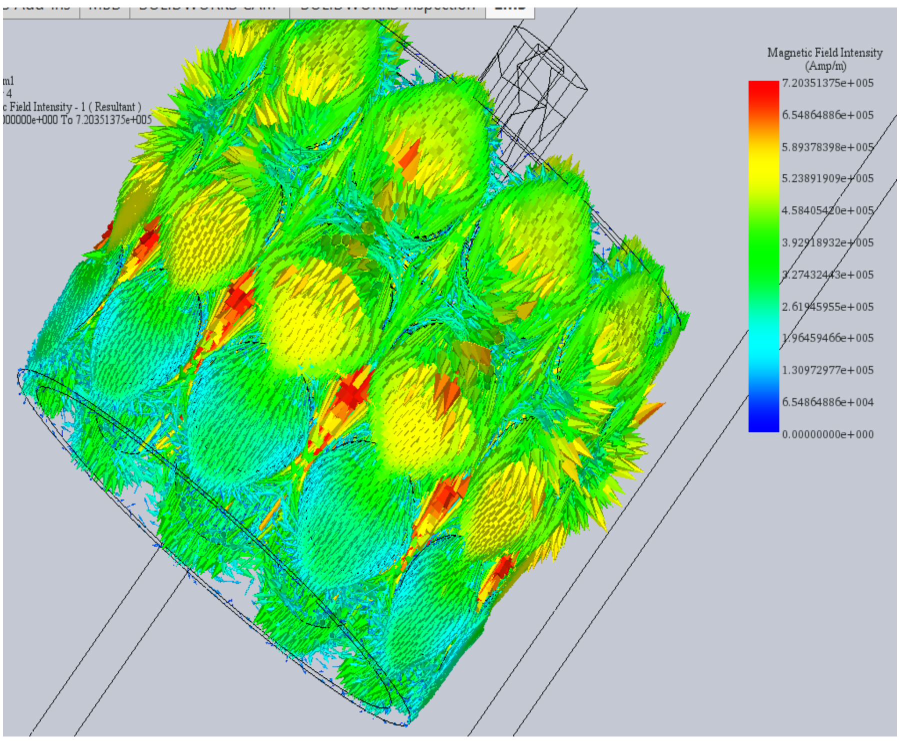


Figure 49: Magnetic flux intensity

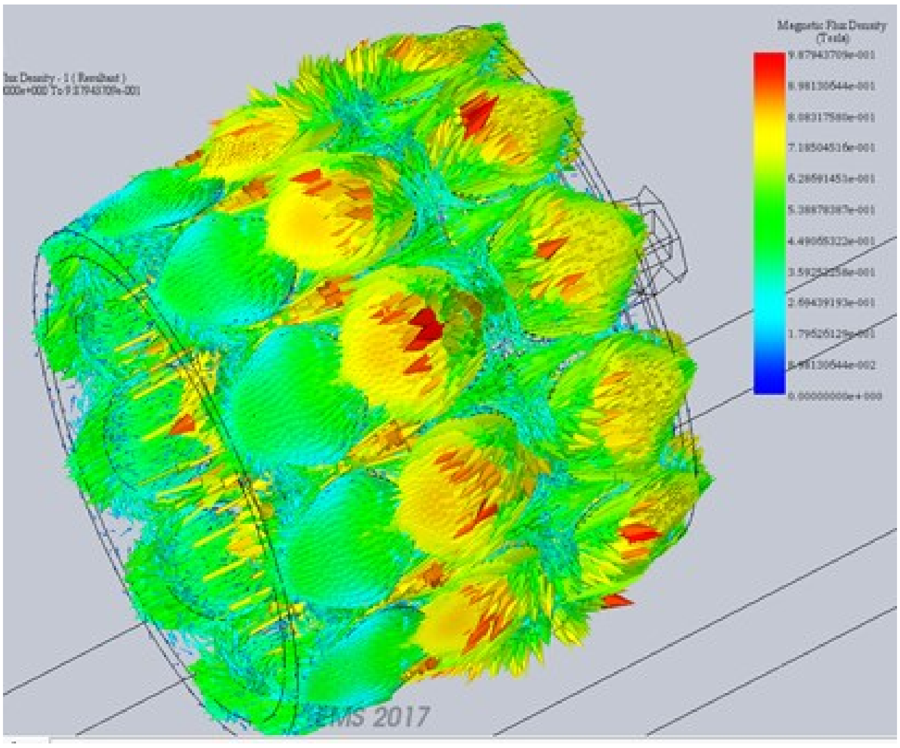


Figure 50: Magnetic flux density

2. Hybrid Design of the Wheels to avoid slippage

   WCR was still having slippage on wet surface, so the design was enhanced to add suction cups in between magnets providing a hybrid adhesion mechanism on the wheels, preventing slippage under wet conditions.

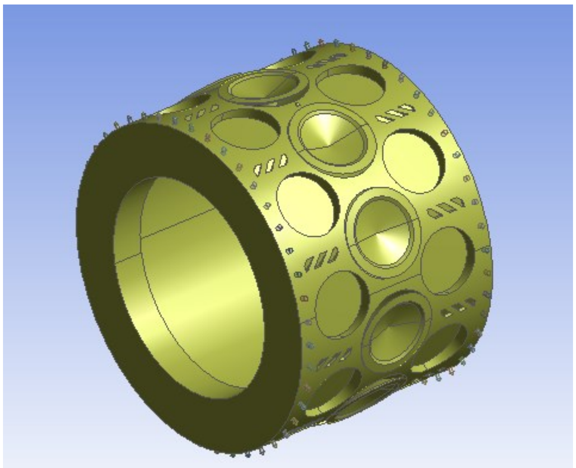


Figure 51: Magnetic Wheels with suction cups